PART 2: OCEANS & CLIMATE CHANGE

LECTURE 3

CLIMATE & GLOBAL WATER CYCLE

“systems ecology” was invented by Alexander von Humboldt. (first realize that differences in community structure are dictated by physical and chemical environment.

Climate: (=/= weather)

- The generally prevailing weather conditions, averaged over at least 30 years.
- The state factor that most strongly governs the global distribution of biomes.
- Is defined by earths energy balance (input= sun energy)
- Determines distribution of terrestrial biomes through water content and temperature.
  (in America from west to east coast gets drier cause more rain in west)
  Temperature + water determine the rates of biological and chemical reactions → control ecosystem processes (production of organic matter by plants, decomposition…)

ENERGY BALANCE OF SUN AND EARTH:

The *temperature* of a body determines the wavelength of energy emitted.

- **Sun:** (source of all of earths E) high temperature (6000K) emits high energy shortwave radiation (infrared) wavelengths of 300-3000nm	- **Earth:** (emits absorbed energy) Low surface temperature (288K) Low energy longwave radiation Wavelength of 3000-30.000K)

The atmosphere is made up of compounds (CH4, N2O, O2, O3, CO2, H20) that absorb light differently. All together, they absorb some of suns energy but not of all wavelengths, so theres some incoming solar radiation.

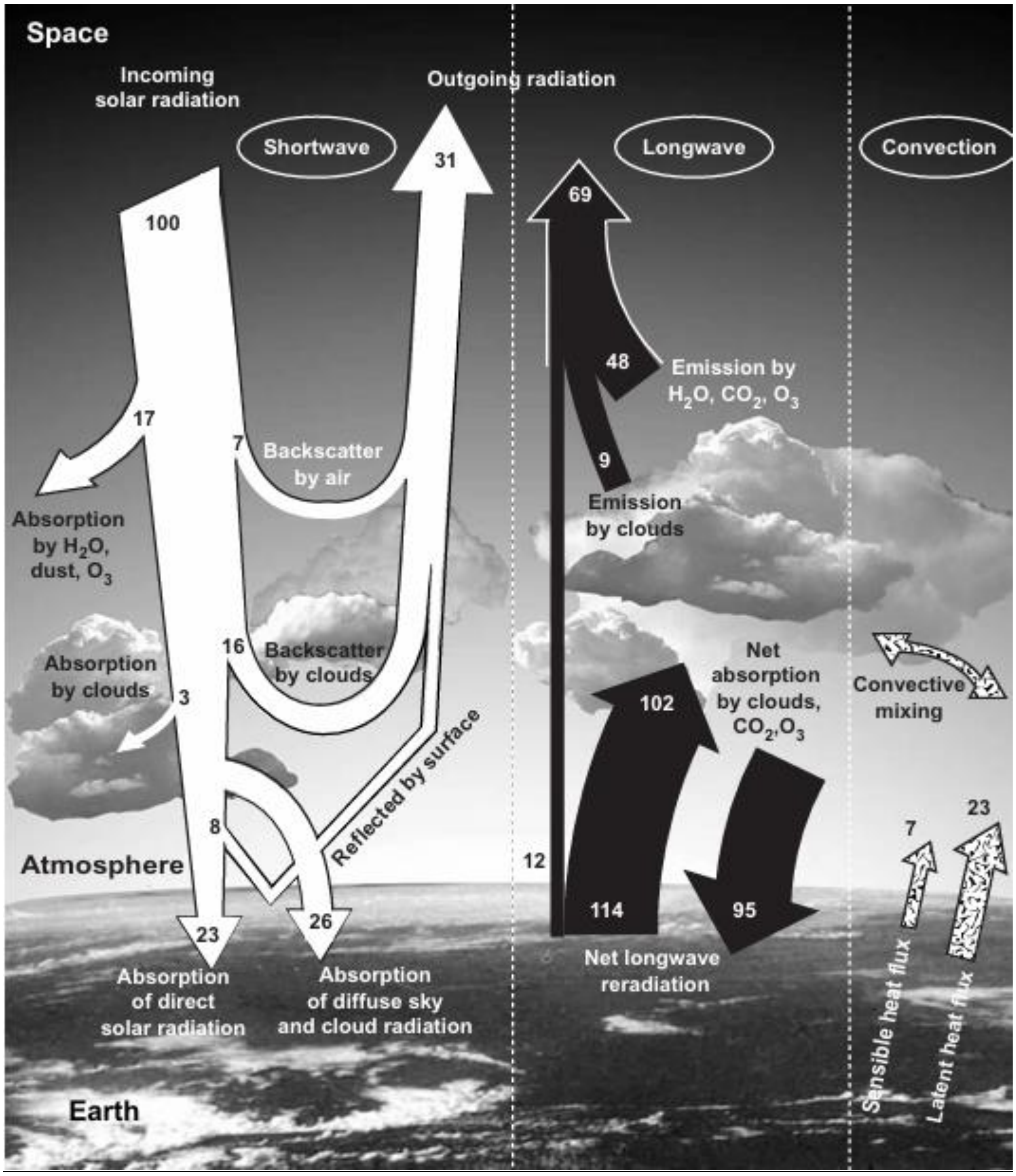
The atmosphere absorbs terrestrial radiation more effectively than solar radiation → so atmosphere is heated from below.

EARTHS RADIATION BUDGET:

How much energy Earth gets from the Sun and how much energy the Earth system radiates back to outer space as invisible light.

If absorbed sunlight = emitted heat, temperature doesn't change - radiation budget is in balance.

*Radiation balance is negative in southern hemisphere (more outgoing than incoming) and positive in northern.



100% emitted by sun

31% reflected back by backscatter

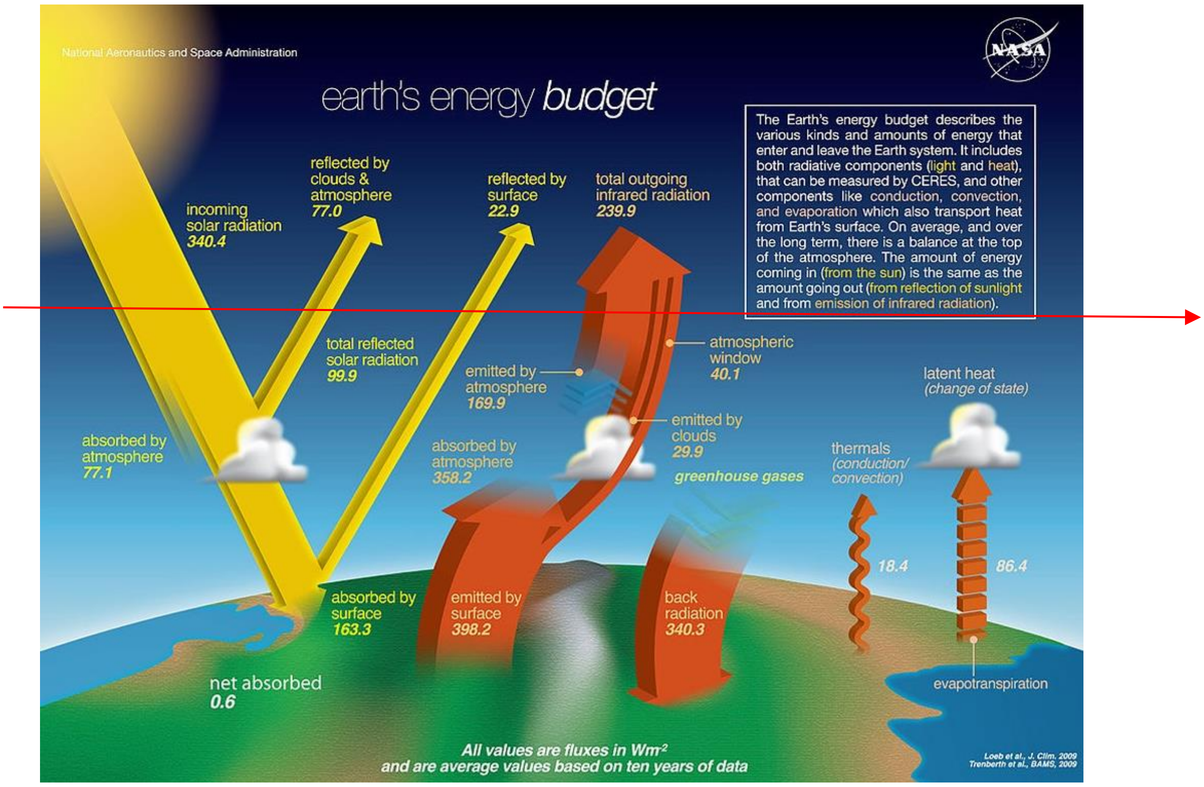
- 16% by clouds
- 7 % by air molecules, dust, haze
- 8% by earths surface)

20% absorbed by atmosphere (ozone at top, clouds at bottom)
49% reaches earth.

On average, and over long terms, there’s a balance of energy at the top of the atmosphere.

(albedo = reflectivity of surface, expressed as fraction of the incoming light being reflected)

BALANCING THE BUDGET:


National Aeronautics and Space Administration
NASA
earth's energy budget
reflected by clouds & atmosphere 77.0
incoming solar radiation 340.4
reflected by surface 22.9
total outgoing infrared radiation 239.9
total reflected solar radiation 99.9
emitted by atmosphere 169.9
atmospheric window 40.1
latent heat (change of state)
absorbed by atmosphere 77.1
absorbed by atmosphere 358.2
emitted by clouds 29.9
greenhouse gases
thermals (conduction/ convection)
18.4
86.4
absorbed by surface 163.3
emitted by surface 398.2
back radiation 340.3
net absorbed 0.6
evapotranspiration
Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009

The Earth's energy budget describes the various kinds and amounts of energy that enter and leave the Earth system. It includes both radiative components (light and heat), that can be measured by CERES, and other components like conduction, convection, and evaporation which also transport heat from Earth's surface. On average, and over the long term, there is a balance at the top of the atmosphere. The amount of energy coming in (from the sun) is the same as the amount going out (from reflection of sunlight and from emission of infrared radiation).

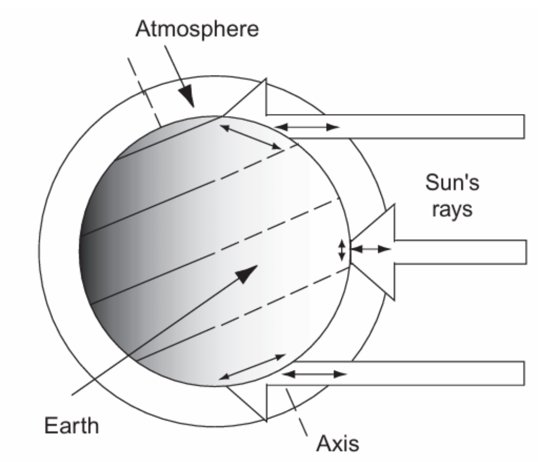
All values are fluxes in Wm^{-2} and are average values based on ten years of data

At top of atmosphere: 0 to be stable
+ sunlight in (100)
- sunlight reflected from clouds/atmosphere (22.6)
- sunlight reflected from surface (6.7)
- IR emission (70.5)

equilibrium T = -18C
(w/o atmosphere, earth would be ice)

At earths surface: 0 to be stable
+ sunlight absorbed (48)
- IR emission (117)
+ IR back radiation, greenhouse effect (100)
- thermals (5.4)
- evotranspiration (25.4)

equilibrium T = 15C



Ingoing:
Atmosphere and angle effects on solar input at different latitudes: (uneven heating is the fundamental cause of atmospheric circulation)

- At poles the path is longer (energy can be absorbed and reflected more than in equator.

Outgoing:
Different albedo depending on the surface.

- Ice + snow reflect (high albedo).
- Oceans + land absorb.

Chemical composition of the atmosphere:
Determines its role in Earths energy budget.

- Energy **absorbing gasses** (CO2, N2O, CH4, CFC's)
- Production of **aerosols**: small nuclei that **reflect** light
  - Atmospheric dust
  - Sea salt (H2SO4)
  - Volcanic H2S + bio activity in oceans (DMS)
  - Small organic molecules
- Water condensation around aerosols → **cloud** forms.

Clouds reflect sunlight → cool
(only when sun shines = day+ summer)

Clouds absorb heat radiation → heats (net impact mainly when sun doesn't shine)

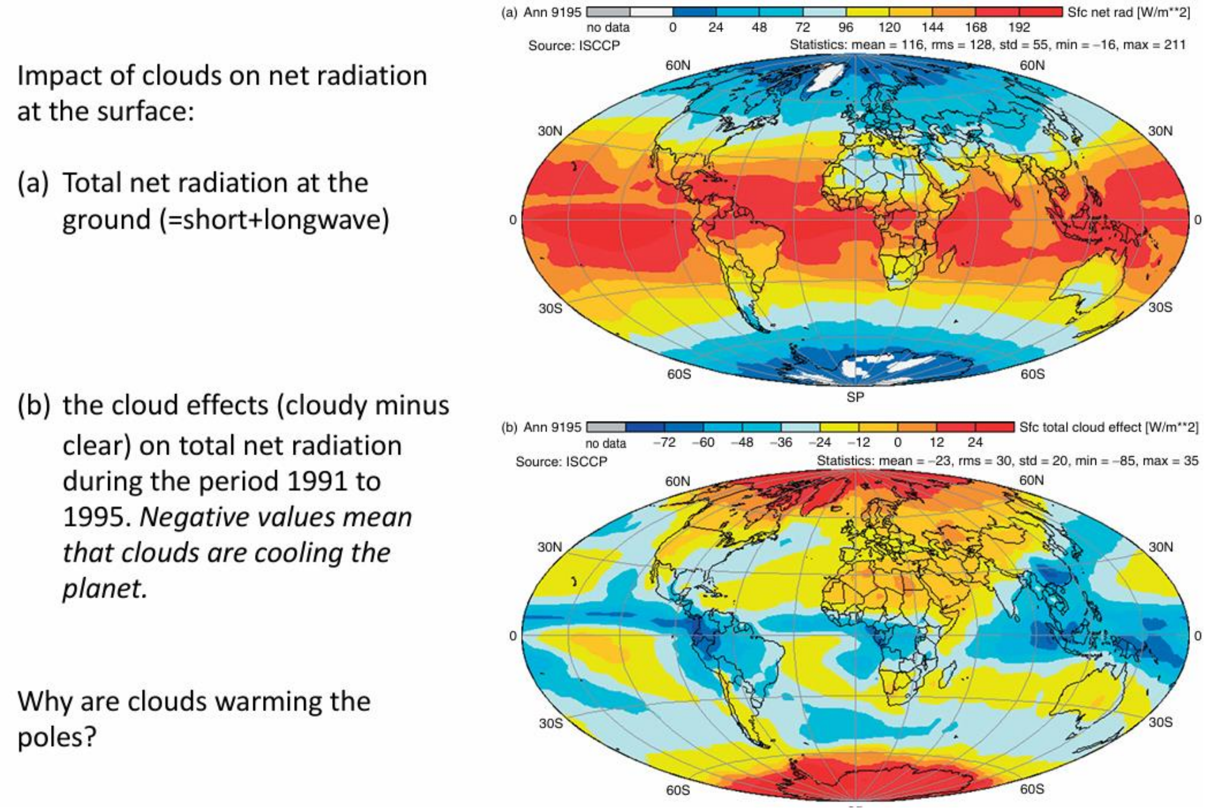
Net effect cloud: moderate T.
- colder during day, warmer at night
- less warm in summer, less cold during winter
- less hot in tropics, less cold at poles

CLOUDS: reflection of sunlight + absorption of heat because they're full of water.
Clouds reduce incoming + outgoing radiation.
Net effect: cool off earth but large uncertainties and regional differences.

- Cool off earths surface → reflect incoming sunlight.
- Warm earths surface → absorbing heat emitted from the surface and re-radiating it back down to the surface.
- Warm OR cool earths atmosphere → absorb heat emitted from the surface and radiate it to space.
- Warm + dry earths atmosphere and supply water to the surface → precipitation.

* Clouds are created by the motions of the atmosphere that are caused by the warming or cooling due to radiation and precipitation (processes they do) → feedback.

* desert: no clouds
- day time: no cloud to reflect back (very hot).
- night time: no cloud to maintain heat (very cold).



Impact of clouds on net radiation at the surface:

(a) Total net radiation at the ground (=short+longwave)

(b) the cloud effects (cloudy minus clear) on total net radiation during the period 1991 to 1995. *Negative values mean that clouds are cooling the planet.*

Why are clouds warming the poles?

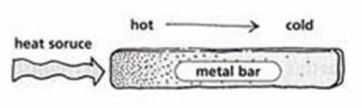
(a) Ann 9195
Sfc net rad [W/m**2]
no data
0 24 48 72 96 120 144 168 192
Source: ISCCP
Statistics: mean = 116, rms = 128, std = 55, min = −16, max = 211
60N
30N
0
30S
60S
SP
(b) Ann 9195
Sfc total cloud effect [W/m**2]
no data
−72 −60 −48 −36 −24 −12 0 12 24
Source: ISCCP
Statistics: mean = −23, rms = 30, std = 20, min = −85, max = 35

Why are clouds warming the poles? Ice in poles reflects → if there's clouds the heat from earth is captured (greenhouse effect higher at poles)

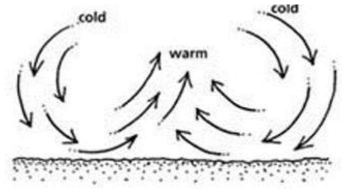
Exchange of absorbed energy:

Four processes of heat loss:

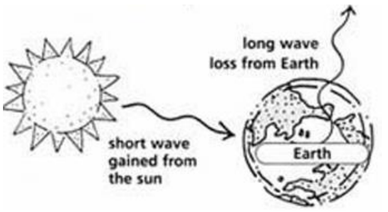
1. Conduction:
   From molecule to molecule



2. Convection:
   Fluid movement of heated air.
   (boiling water)



3. Radiation:
   Energy passing from one object to another without a connecting medium.

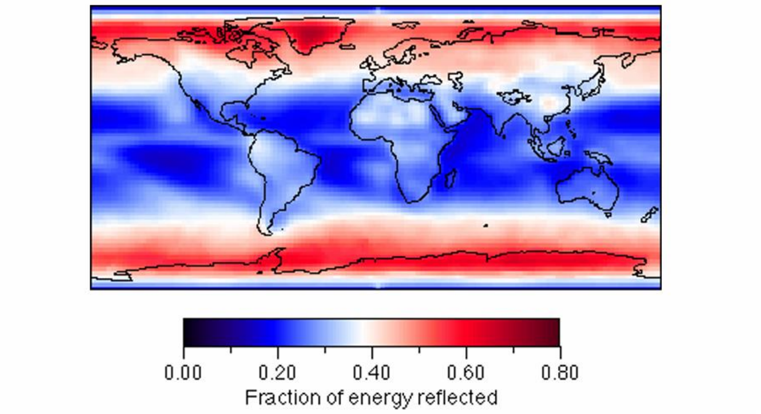


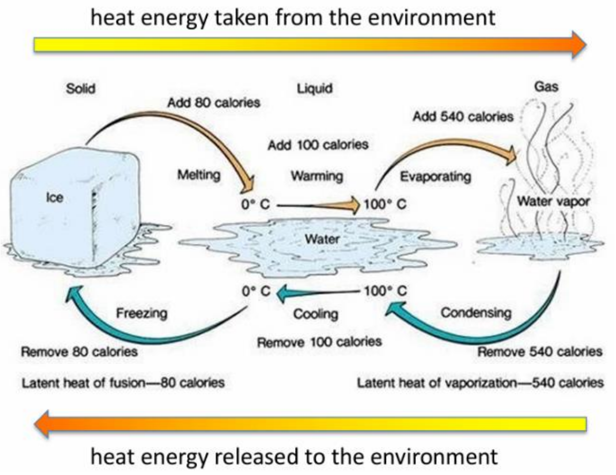
4. Evaporation:
   Chemical energy due to water phase changes (evaporation, condensation…) and water vapour transfer.

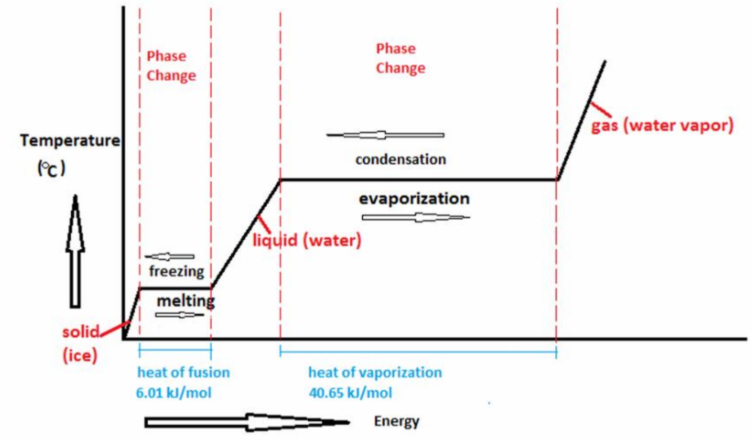
Sensible heat: the heat that can be felt. Its the energy moving from one system to another that changes the temperature.

Latent heat: the heat needed to change phase (from one form of matter to another), which doesnt change temperature.

The reflectivity or *albedo* of the Earth at the top-of-the-atmosphere (TOA): combination of surface albedo and cloud albedo







Formation of ice releases heat (like at the poles)
Condensation releases a lot more heat (clouds)

Poles: high albedo (ice reflects)

In shouth America: intermediate because its a rainforest (lots of clouds and rainfall due to evaporation).

STRUCTURE OF THE ATMOSPHERE:

P = pressure
h = height
ρ = density
g = gravitational acceleration

Decline of air density follows that of pressure: **$dP/dh = -\rho g$**

(warm air is less dense → P declines with h more slowly than for cold air)

Troposphere: heating by long-wave radiation + sensible + latent heat
Stratosphere: heated from top due to absorption of UVR by ozone (O_3)

Temperature commonly decreases with height, because:

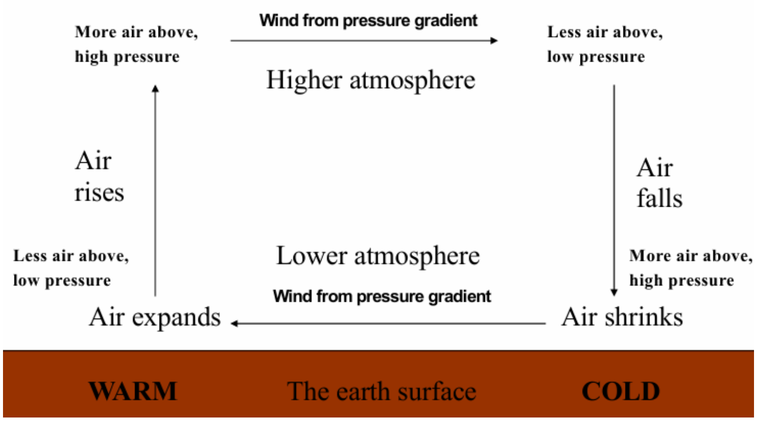
- The atmosphere is heated from the surface
- Rising air expands + cools (adiabatic) T decrease ~-10 °C /km ("dry adiabatic lapse rate")
- With greater moisture content, more latent heat is released
- Result: Global mean is -6.4 °C /km (in mountains radiation is absorbed at greater heights → -4.2 °C /km)

ATMOSPHERIC CIRCULATION:

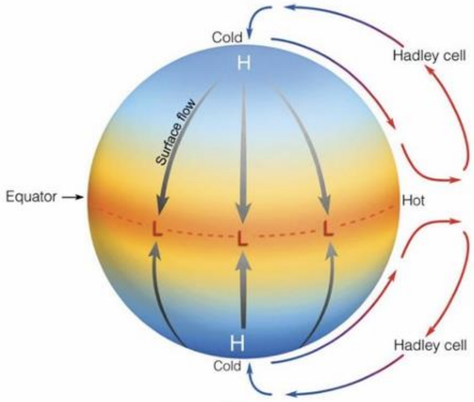
Due to uneven heating of earths surface.

Atmospheric pressure is mainly caused by weight of overlying air.

Wind is air movement caused by pressure gradients. (rises when warm, like at equator, and moves from high to low Pressure)


More air above, high pressure
Wind from pressure gradient
Less air above, low pressure
Higher atmosphere
Air rises
Air falls
Less air above, low pressure
Lower atmosphere
More air above, high pressure
Wind from pressure gradient
Air expands
Air shrinks
WARM
The earth surface
COLD

Surface wind should blow from poles to equator



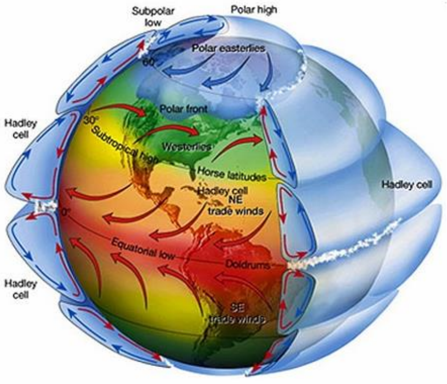
When warm air rises, it creates a low P zone at the surfaces and pushes air upwards through **convection.**

As air rises, it cools and spreads out towards **higher latitudes** (around 30C north and south)
BUT, it doesn't continue all the way to the poles because of earths rotation (**coriolis effect**) and the way **heat** is distributed across the planet.

At around 30C latitude, the now cooler air sinks back towards the surface, creating a high pressure zone. This air is dry because most of the moistures been lost as precipitation when it was rising and cooling near the equator.

Once it reaches the surface around at 30C latitude, it flows back towards the equator. These winds are deflected by earths rotation, creating trade winds that blow from east to west in the tropics.

..however, the upper air is cooled by thermal emission and the cold and heavy air falls down to Earth before the poles are reached.

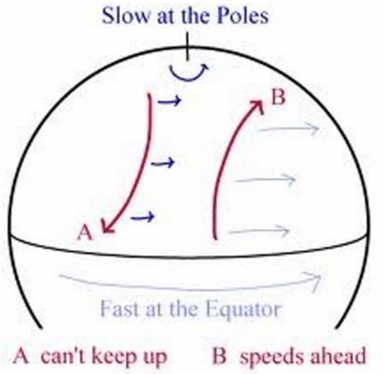


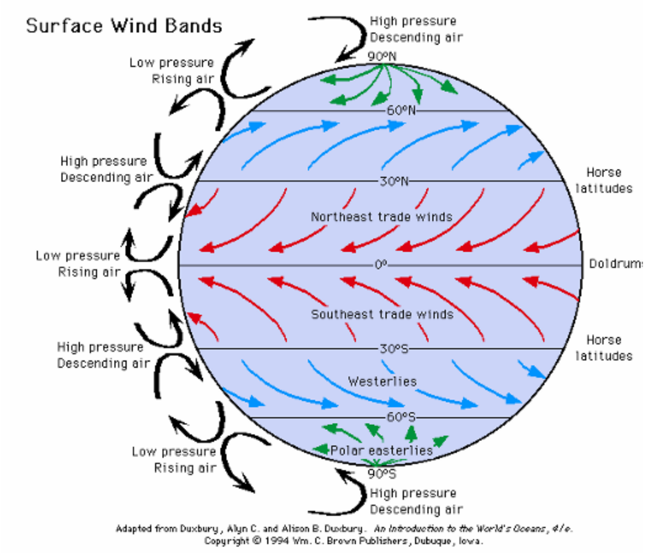
... and wind direction turns by earth rotation (Coriolis force)

Coriolis force: dictates direction of air + ocean currents.

Results from the earth turning, wind deviation is

- On northern hemisphere: clockwise
- On southern hemisphere: anti clockwise





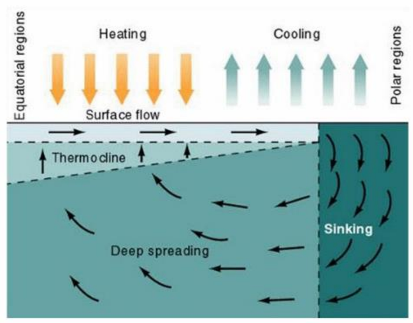
Adapted from Duxbury, Alyn C. and Alison B. Duxbury. *An Introduction to the World's Oceans, 4/e.* Copyright © 1994 Wm. C. Brown Publishers, Dubuque, Iowa.

Vertical movement results from temperature differences

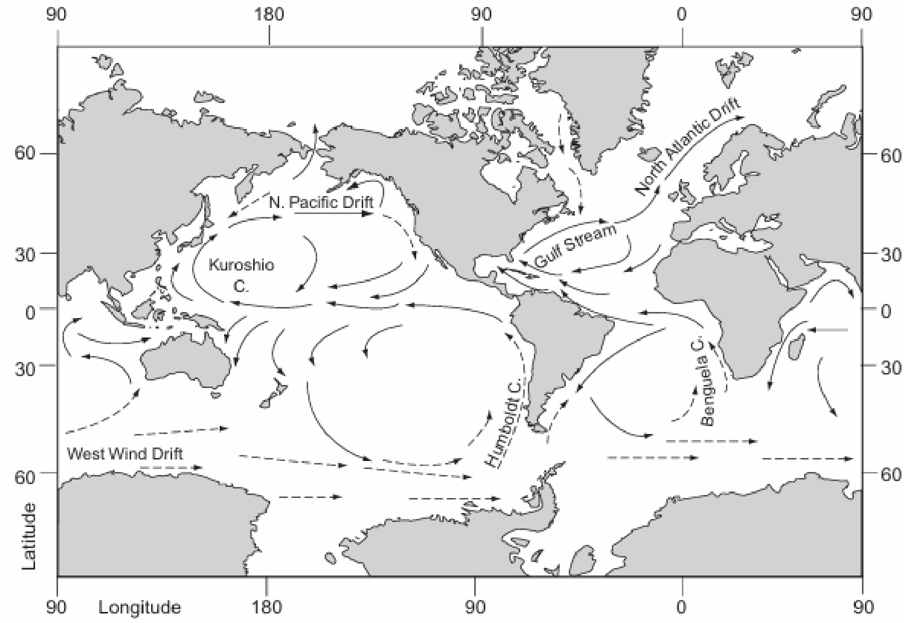
Horizontal movement result from pressure differences

3 wind cells per hemisphere → bands of low and high pressure

Ocean circulation plays a critical role in heat transfer.



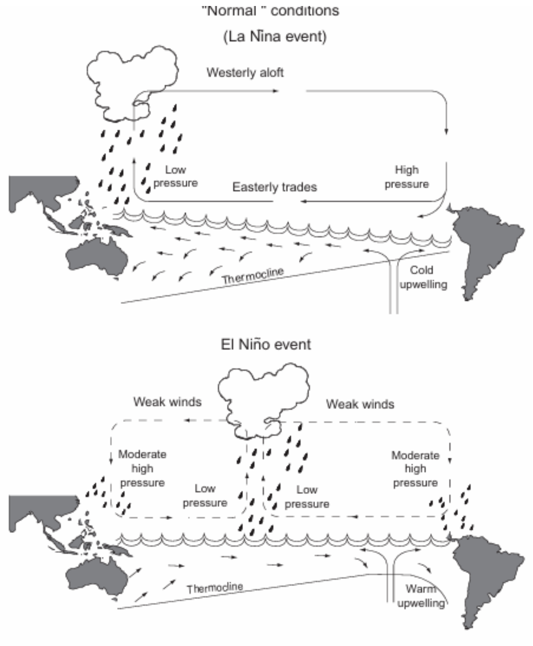
Global temperature is estimated from radiation equilibrium but its more complicated locally. Energy from the radiation imbalance (heat) is transported by wind and ocean currents from the equator to the Poles. (extra reason why clouds warm the poles)



Warm currents: solid lines

Cold currents: dashed lines

El Niño y La Niña: part of a natural climate pattern in the Pacific Ocean that affects weather



El Niño = Warmer Pacific waters = More rain in the Americas, droughts in Asia/Australia.

La Niña = Cooler Pacific waters = More rain in Asia/Australia, drier conditions in the Americas.

1. El Niño: (returns every 3-7 years)

-Waters in the central and eastern Pacific become warm.

- Normally, the trade winds (winds that blow east to west) push warm water toward Asia, but during El Niño, these winds weaken, allowing warm water to spread east toward the Americas.

- This warming can cause extreme weather, like heavy rainfall and flooding in places like South America and drought in places like Australia and Southeast Asia.

2. La Niña:

- Waters in the central and eastern Pacific become unusually cool.

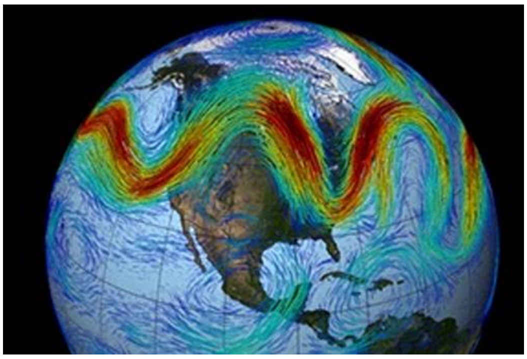
- Trade winds are stronger, pushi warm water to Asia allowing cool water to rise in America.

- Causes rainfall and storms in Asia and Australia, and drier conditions in parts of America.

* upwelling: winds blowing across ocean surface → push water. Water rises from below to replace it.

LANDFORM EFFECTS ON CLIMATE:

The uneven distribution of land and oceans creates an uneven pattern of heating that modifies the general latitudinal trends in climate.



- High pressure over open oceans
- Seasonal differences of pressure systems over land
- Mountain ranges
- Deviates in wind direction → planetary wave

Example: **Rossby waves** are large, slow-moving waves in the atmosphere and oceans that flow about 10km above ground (between the troposphere and the stratosphere). They play a big role in shaping weather patterns.

- Planetary waves are not static.
- Changes in location or in number of waves alter regional patterns of climate.
- Changes in circulation pattern are referred to as climate modes.

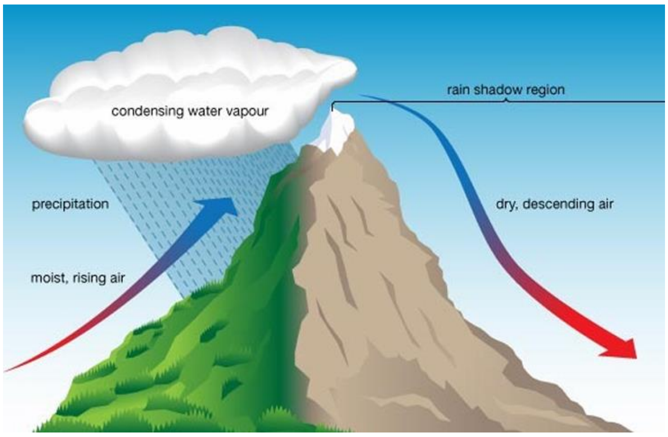
- In the atmosphere: Rossby waves form in the jet stream (fast-moving current of air high in the atmosphere). These waves meander north and south as they move from west to east. When they bend, they push air masses around → changes in weather.
    - When the wave dips down, it brings colder air from the poles toward the equator.
    - When the wave rises, it can pull warmer air from the tropics toward the poles.
- In the oceans: they move much more slowly. They affect the movement of large bodies of water and can influence long-term ocean currents and climate patterns.

Rain shadow effect: when mountains block rain from reaching one side.

- Moist air from the ocean hits a mountain range and is forced to rise.

- As it rises, the air cools, and rain falls on the side facing the ocean (windward side).

- After crossing the mountains, the now dry air descends, warming up and creating dry conditions on the other side (leeward side).



VEGETATION INFLUENCES ON CLIMATE:

The reflectivity or albedo of earths surface varies with the material that covers it.

The earths average albedo (atmosphere+surface) is about 30%

Albedo: dry soil > wet soil > grasslands > deciduous forests > coniferous forests

Bowen ratio = de ratio sensible: latent heat flux
“determines the strength of linkage between energy budget and the hydrological cycle, because it is inversely related to the proportion of net radiation that drives water loss from ecosystem”

→ to compare how energy is used:

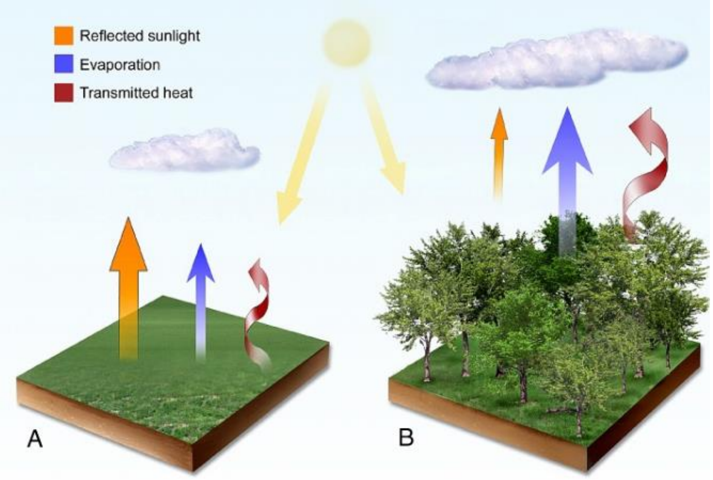
1. Heating the air (sensible heat)
2. Evaporating water (latent heat)

Ratio varies: 0.1 for tropical oceans, 10 for deserts.

- If Bowen ratio is high, more energy is used to heat the air (in dry places, like deserts).

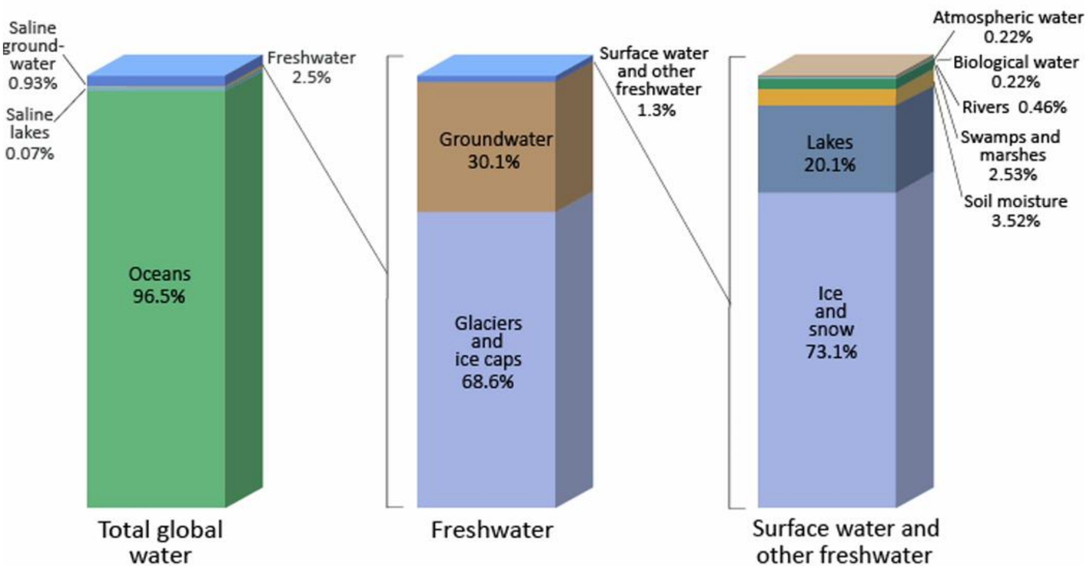
- If Bowen ratio is low, more energy is used to evaporate (humid, near oceans or forests).

Surface roughness affects heat exchange: in woods more turbulence than over grass land.

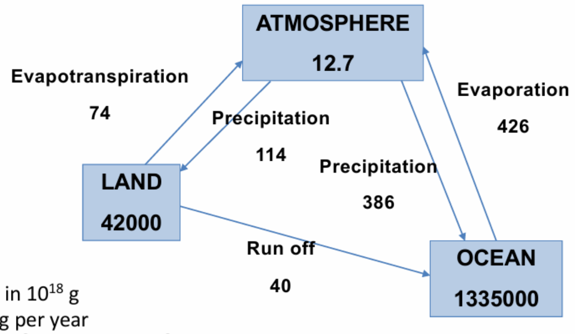


WATER BALANCE:

THE GLOBAL WATER CYCLE:



Hydrological cycle:



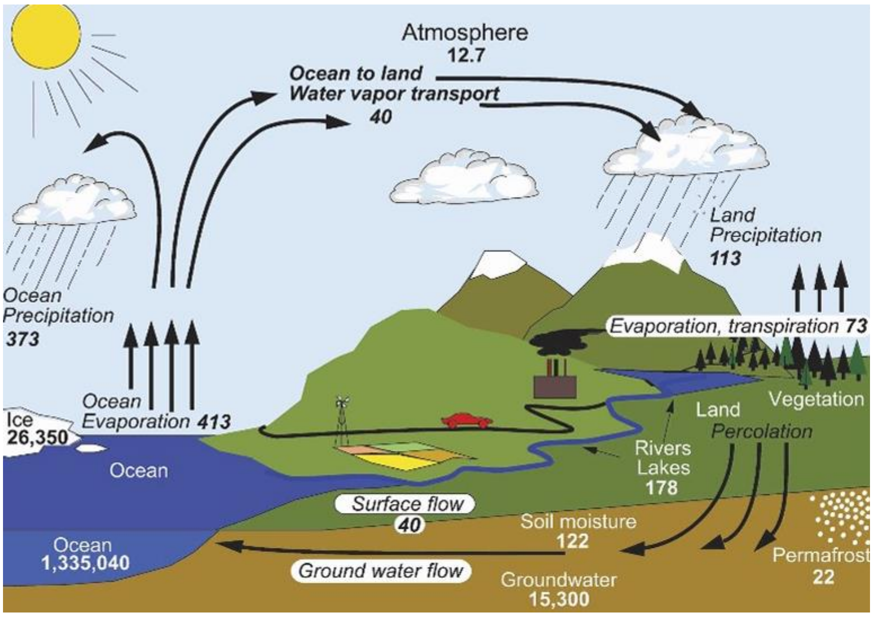
Water masses in 10^{18} g
Fluxes in 10^{18} g per year
1 km^3 = 1000^3 m^3 = 100.000^3 cm^3= 10^{15} g
So 10^{18} g = 1000 km^3

evaporation + precipitation dominate.

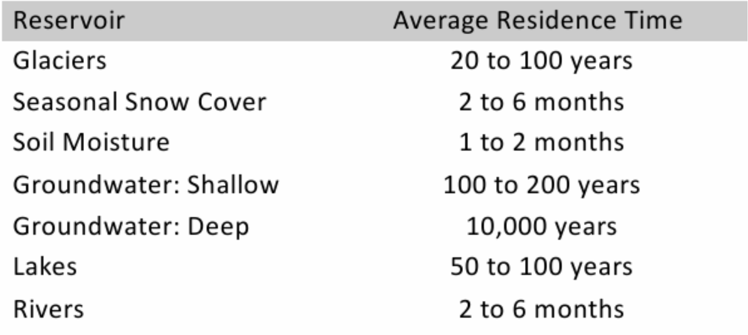
All water comes from the ocean

Residence time= mass / outgoing flux.

- In atmosphere:
  13 / (114 + 386) =
  0.025 years = 9 days.



Typical residence time of water found in various reservoirs



Reservoir	Average Residence Time
Glaciers	20 to 100 years
Seasonal Snow Cover	2 to 6 months
Soil Moisture	1 to 2 months
Groundwater: Shallow	100 to 200 years
Groundwater: Deep	10,000 years
Lakes	50 to 100 years
Rivers	2 to 6 months

The water cycle on land starts with precipitation

* **Low Pressure Systems** = Air rises, causing clouds, precipitation, and storms (bad weather).

High Pressure Systems = Air sinks, causing clear skies and stable weather (good weather).

Why does water (sometimes) precipitate? → it condenses into droplets when the air cools down

- Cooling by thermal emission (from the ground): when temperature drops, the air cools down and water vapor in the air can condense into tiny droplets (fog)
- Cooling by rising and expanding air in the atmosphere (clouds)

Why should air rise?

(due to differences in T and P → create conditions where lighter, warmer air gets pushed up by heavier, cooler air).

1. lifted in low pressure systems (warm areas, tropics and mid latitudes)

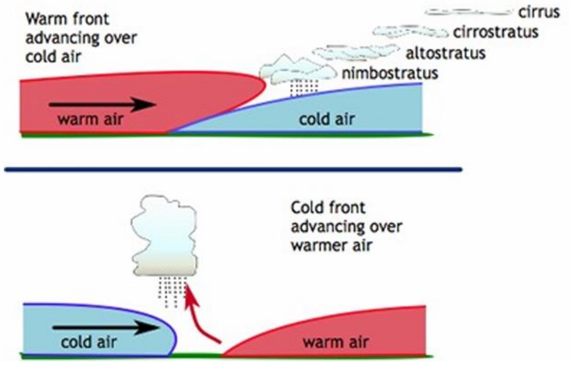
In places where the air pressure is low (tropical regions or mid-latitudes), the warm air rises because it's lighter. As it rises, it cools down and can lead to cloud formation and rain.

2. Displaced by cool, heavy air

Warm fronts produce clouds when warm air replaces cold air by sliding above it.

Cold fronts occur when heavy cold air displaces lighter warm air, pushing it upward.

(when cold air moves in, it pushes the warm air up because its heavier (more dense)



3. Unstable atmosphere with warm, light air below cold, heavy air.

When warm, light air is underneath cooler, heavier air, the warm air rises because it's less dense.

This can create scattered clouds if the atmosphere is unstable, as the warm air keeps rising through the cooler air above it.

Rain intensity versus temperature:

- Warm air contains more water vapour: +7% /1°C
- Theory: rain intensity also increases with 7% /1°C
- Observations: rain intensity increases with 14% /1°C (result of positive feedback)

Positive feedback:

1. Warmer air contains more water → cloud contains more water
2. More condensation = latent heat flux = air heats up
   (evaporation absorbs heat, condensation releases)
   (the release of energy warms the surroundig air, fueling cloud formation)
3. Increased moist convergence into the cloud
   As air in and out of the cloud heats up, it rises faster. This upward movement of air creates a low pressure zone near the surface, which draws in more moist air from the surroundings (moist convergence)

Showers become heavier due to climate change

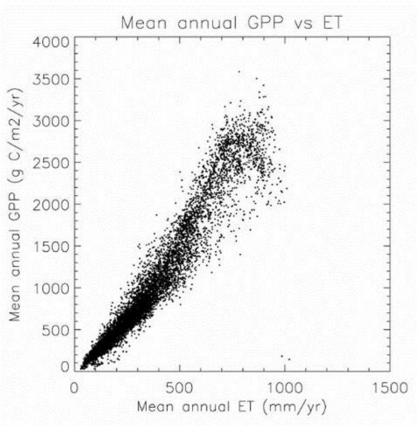
* subtropical oceans are the main source of water vapour.
* Seasonal variation:

- Summer rain: low latitude (close to equator)
- Winter rain: ~ 40
- Autumn/late summer: > 40

WATER AVAILABILITY:
Evaporation is a measure of ecosystem functioning because evaporation of water and CO2 uptake are both regulated by the stomata of plant leaves.

Gross Primary Production versus Evapotranspiration.
GPP is strongly correlated to ET.

- GPP: amount of energy plants capture.
- ET: evaporation + transpiration (water released as vapor by plants)

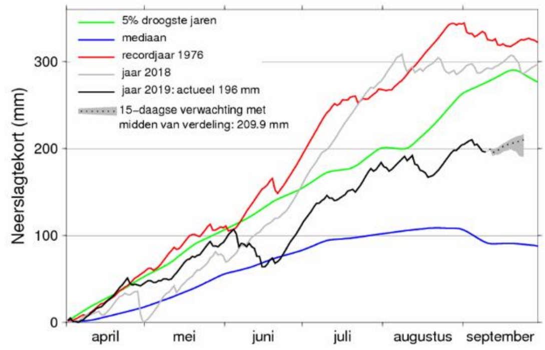


As plants grow they capture more energy + release more.
Forest with high GPP and low ET → efficient at turning sunlight into energy without loosing too much water.
* soil water is needed when evaporation exceeds precipitation.

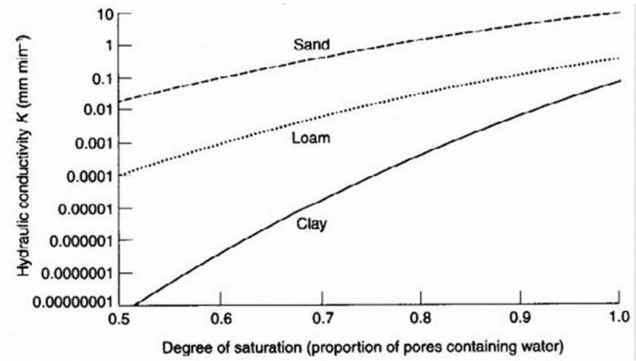
Precipitation deficit = evaporation – precipitation.

- Varies strongly between years.
- An ecosystem must be able to survive the driest years
  → in NL water holding capacity of 300mm is needed.

Soil water shortage:
Soil's water holding capacity is limited almost everywhere.
→ capillary force (water sticks to the smallest pores)
Clay has small pores, so it retains water better than sand.



Hydraulic conductivity:’



Measures the speed with which water moves through a porous medium (like soil)

(with sand, even when dry, water moves through it much faster)

Water retention curve:

water tension increases when the soil dries out.

Ψ is soil water potential

0 is water content

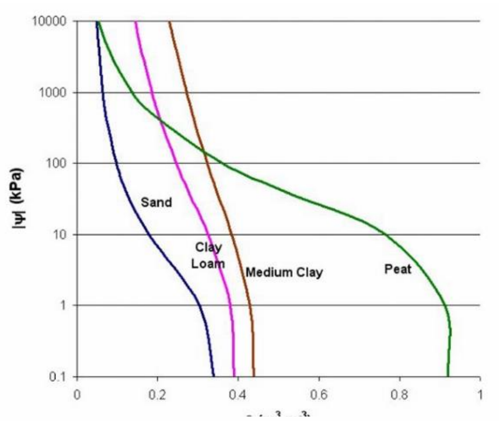
Ψ < |10|: water drains by gravity

For agriculturalcrops: Ψ ~ |10|: field capacity (optimalgrowth)

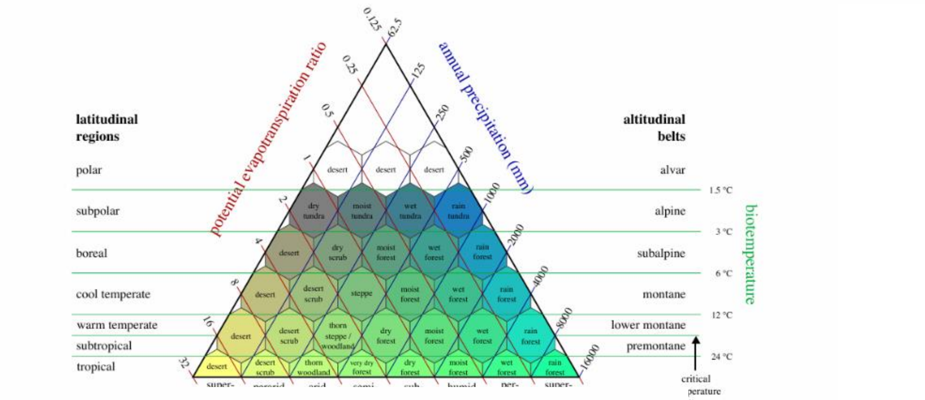
Ψ > |1600|: wilting point

→ Only part of soil water is available for plants

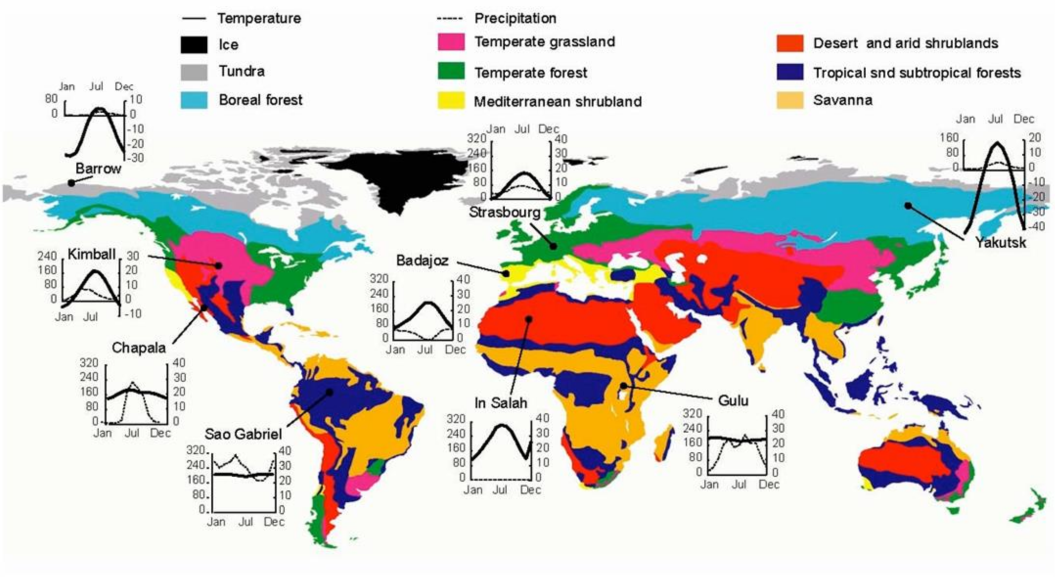
→ Water can limit plant growth, even in years without water shortage



ecosystem distribution:



idge, 1947, 1967)

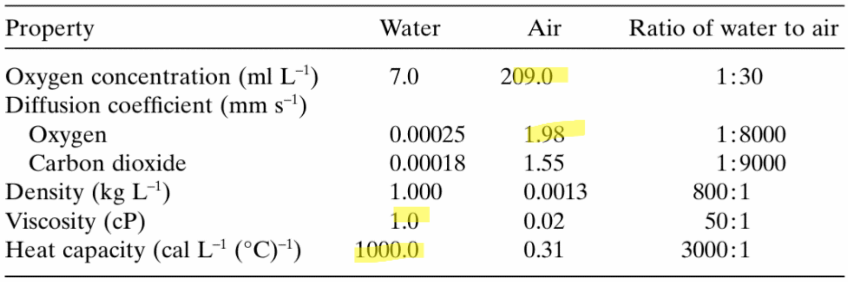


The global distribution of Earth’s major biomes and the seasonal patterns of monthly average temperature and precipitation at one representative site for each biome.

LECTURE 2 – OPEN OCEANS

Biome: topographic/geographic defined area, in which the species are adapted to and limited by the physical environment.

Characteristics of water and air affecting ecosystem processes:



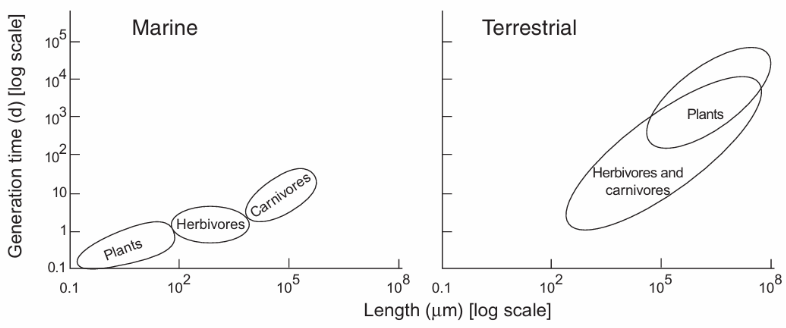
Property	Water	Air	Ratio of water to air
Oxygen concentration (ml L^{-1})	7.0	209.0	1:30
Diffusion coefficient (mm s^{-1})			
Oxygen	0.00025	1.98	1:8000
Carbon dioxide	0.00018	1.55	1:9000
Density (kg L^{-1})	1.000	0.0013	800:1
Viscosity (cP)	1.0	0.02	50:1
Heat capacity (cal L^{-1} (°C)$^{-1}$)	1000.0	0.31	3000:1

- viscosity: size related (very small animals experience viscosity more)

- heat capacity: water has more gradual T change.

- [O2] : easy to get in air (stomata…) → oxidative metabolism gains more E faster.
- Diffusion coefficient (O2, CO2): lower in oceans→ being small is better (more surface area in cell).

Relationship body size and generation time



- plants in terrestrial systems invest a lot to keep themselves upright (structural biomass), but not in oceans so they allocate more to proteins.
- plants determine the habitat structure in terrestrial systems, whereas ocean systems are shaped by physico-chemical gradients.

	Terrestrial	Marine
Surface	• 29% of Earth's surface	• 71% of Earth's surface
Plants	• Sessile • Large structural biomass • mainly carbohydrates • 560 Gton C • 56 Gton C/yr • Average turnover time: 10 year	• Floating • 95% unicellular • Mainly proteins for storage • 2-5 Gton C • 49 Gton C/yr • Average turnover time: 1 week
Animals	free living	Sessile and free living
Biomass Plants : animals	1000 : 1	1 : 30
Foodweb	3 trophic levels	3-6 trophic levels

marine plants produce almost as much C a year because they have a smaller turnover time.

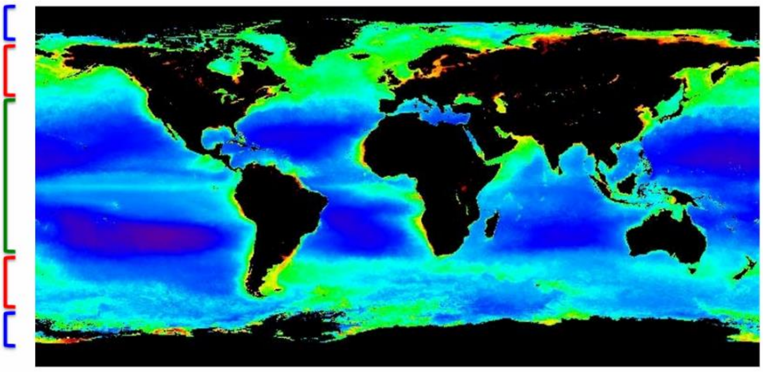
	Terrestrial	Marine
Physical structuring	Plant forms	Vertical light gradient, temperature, nutrients
Density	Overcome gravitation	Overcome viscosity
Temperature	Large variations (daily, seasons)	Buffered
Light	Absorption by vegetation	Absorption by water (max. 400m)
Chemistry	"fresh"	"saline"
Stress factors	Temperature Drought Light	Nutrients Light

Physico-chemical properties:

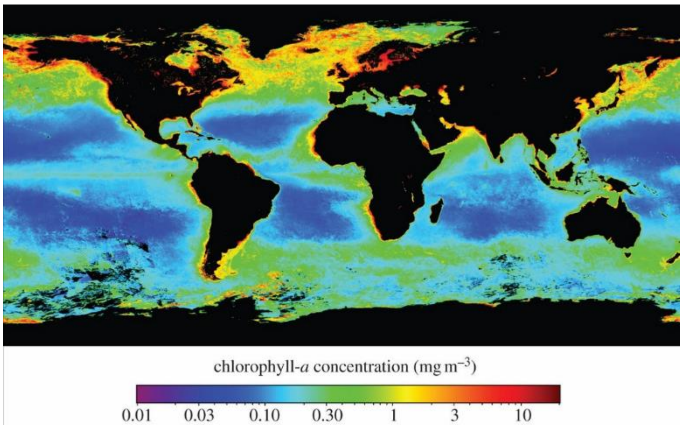
Biogeochemistry: study of the cycles of chemical elements and their interactions with and incorporation into living things. Particular emphasis is placed on the study of carbon, nitrogen, sulfur, and phosphorus cycles.

- 71 % of Earth's surface is covered by oceans and coastal seas
- 60% of humanity lives in coastal areas (< 60 km from the coast)
- Oceans and seas impact on: food supply, natural resources and climate.

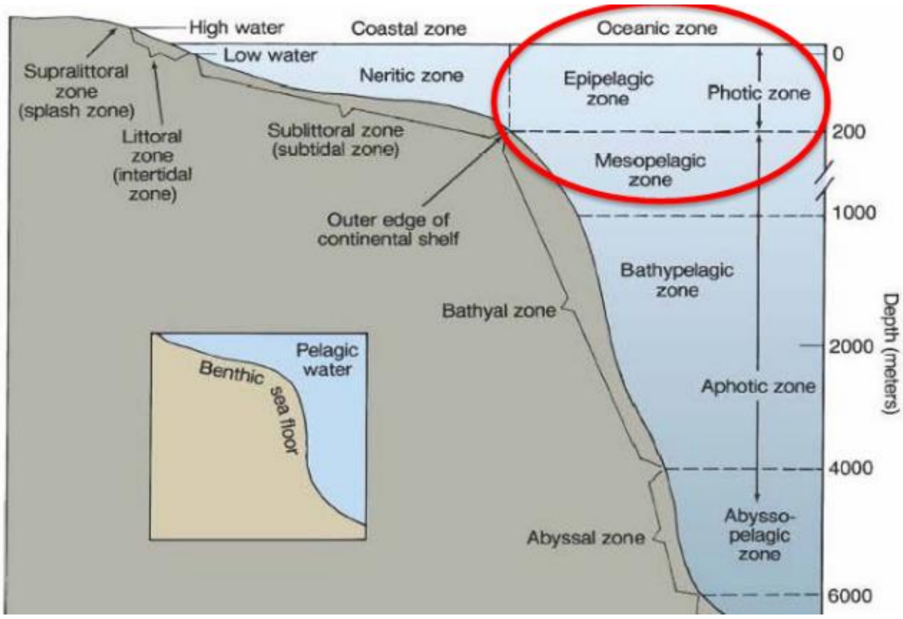
4 main oceanic biomes:
1. trades
2. westerlies
3. polar
4. coastal



CHLOROPHYLL DISTRIBUTION:



Zonation	
By distance from continent	- coastal - oceanic
By light	- euphotic - disphotic - aphotic
By depth	-epipelagic - mesopelagic - bathypelagic - abyssopelagic

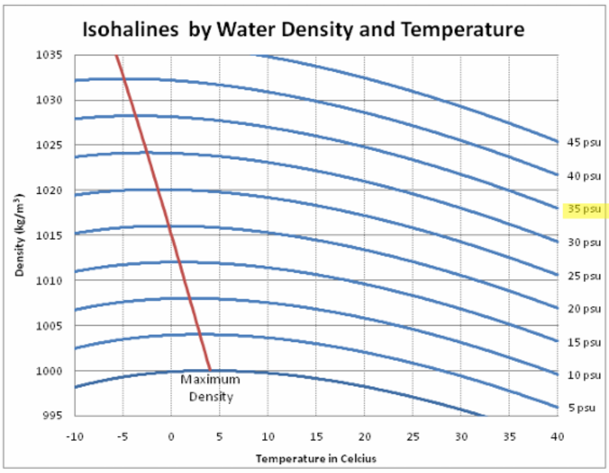


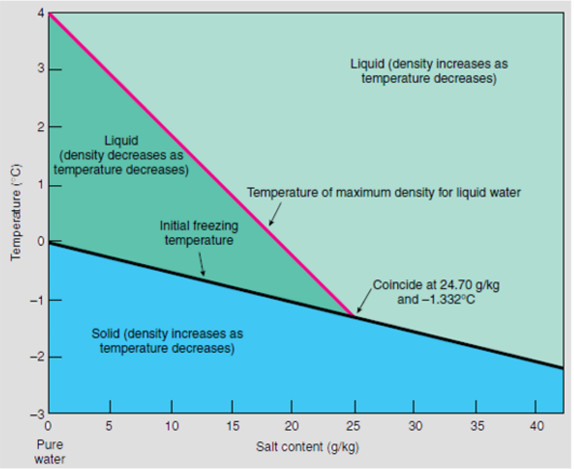
Physico-chemical parameters determining the boundaries of open-ocean ecosystems:

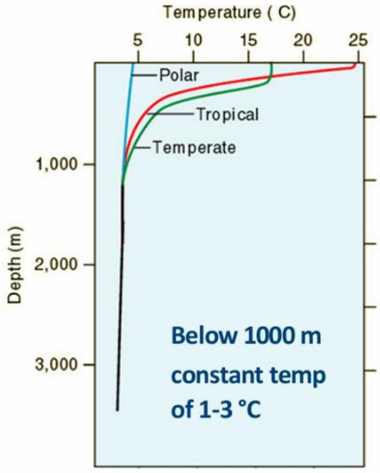
- Temperature + salinity = density
- Wind + Coriolis force + Tidal activity => 3D-current pattern
- nutrient distribution (N, P, Si, Fe)
- light

TEMPERATURE + SALINITY = DENSITY

- Density of water of specific salinity (measured in PSU units).
    - The saltier the water, the denser it becomes → salty water is heavier than fresh.
    - In general, cold water is denser than warm water.
- The temperature of maximum density reduces with increasing salinity.
- fresh water has maximum density when it is not yet frozen, but high salinity water reaches it near freezing point (different molecule expansion behaviour)







Temperature profiles

warm water is lighter than cold water → stratification

- polar
- temperate
- tropical latitudes.

Salinity:

Surface salinity (% salts):

- Fresh water runoff results in salinity decrease
- Evaporation results in salinity increase.

Density:

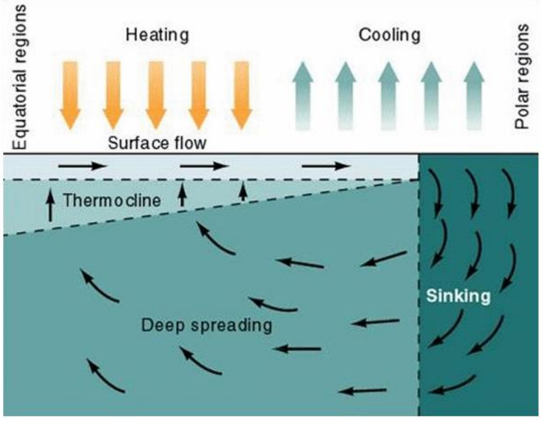
Formation of layers (different water masses) due to variations in T, salinity and wind mixing

- **Thermocline** = depth zone of most rapid T decline
- **Halocline** = depth zone of most rapid salinity change
- **Pycnocline** = depth zone of most rapid density change

Less salinity in surface → RAIN
(lot of rain in equator, so less salinity)

Thermohaline circulation:

- Water heats near equator + cools near Poles.
- Cold water = heavy → sinks
- Sea-ice formation near the Poles: production of brine= heavy → sinks

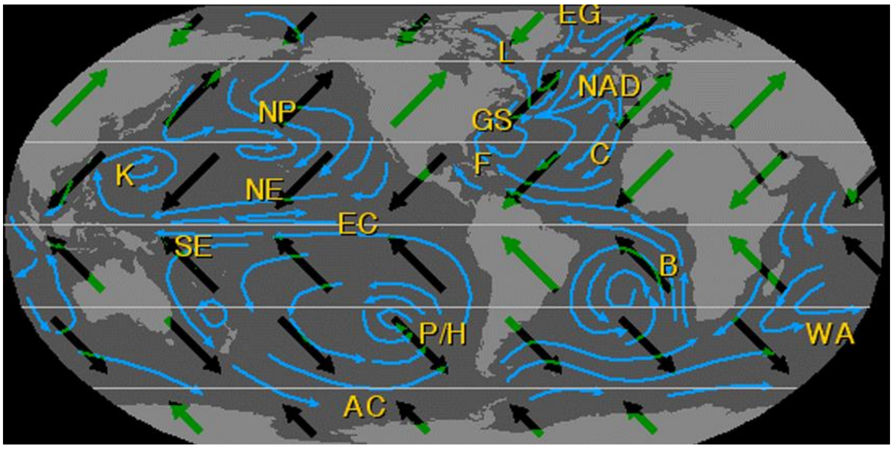


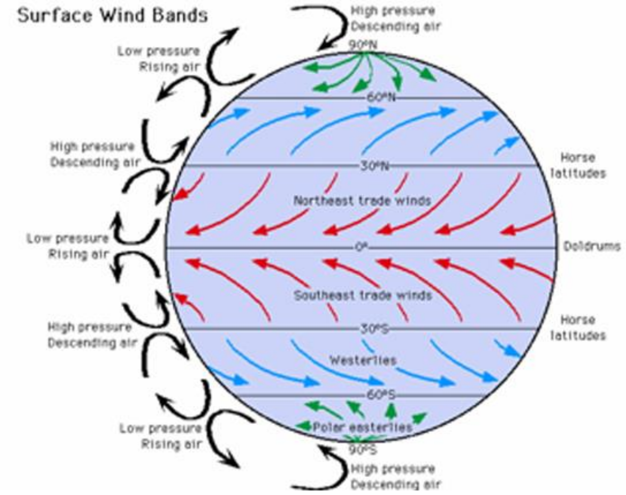
WIND + CORIOLIS

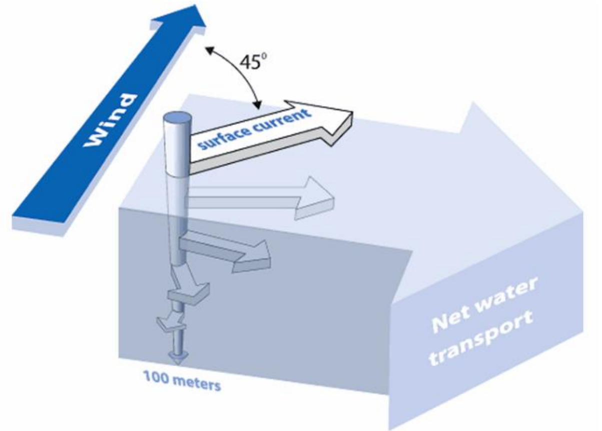
Impact Coriolis effect on circulation patterns:

- Northern Hemisphere: clockwise deviation
- Southern Hemisphere: anticlockwise deviation

General flow patterns of surface waters controlled by wind + coriolis.



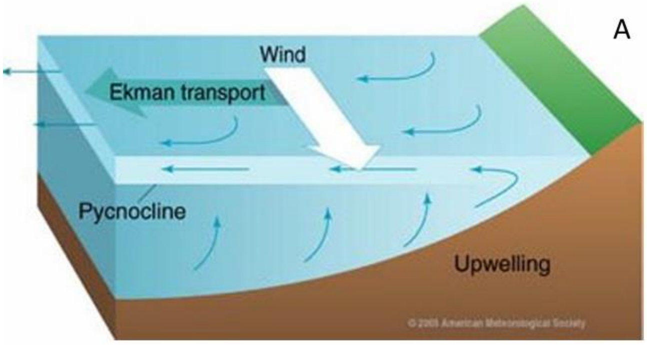


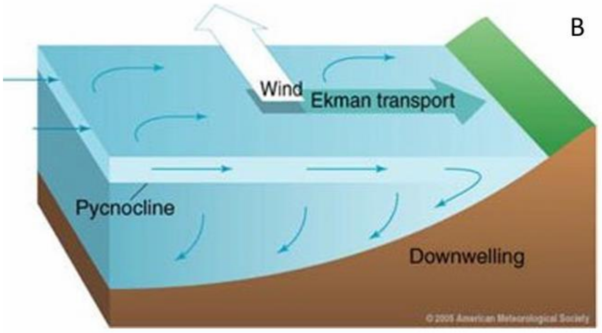


EKMAN SPIRAL: (consequence of the Coriolis effect).

When surface water molecules are moved by the wind, they drag deeper layers of water molecules below them. Like surface water, the deeper water is deflected by the Coriolis effect (to the right in N Hemisphere, to the left in S Hemisphere).
As a result, each successively deeper layer of water moves more slowly to the right or left, creating a spiral effect.
(all pictures are northern hemisphere examples)

When wind blows parallel to the coast, Ekman transport results in surface water moving away from the coast (A) or towards it (B).
Upwelling areas (A) bring nutrients to the surface → increased primary productivity.





Important upwelling areas:

- Peruvian coast (fertilizes phytoplankton → zooplankton → fish)
- Equatorial pacific – RED LINES WIND PIC (trade winds of the two hemispheres converge near the equator, the consequent Ekman transport away from the equator gives rise to upwelling)

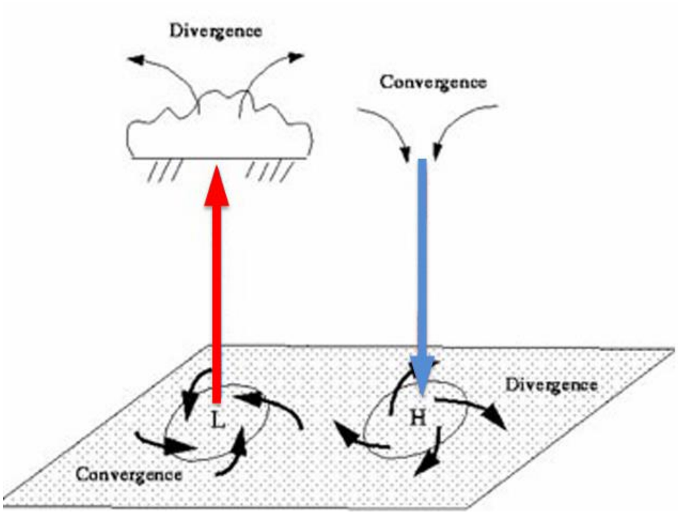
Atmospheric patterns around high-and low pressure systems

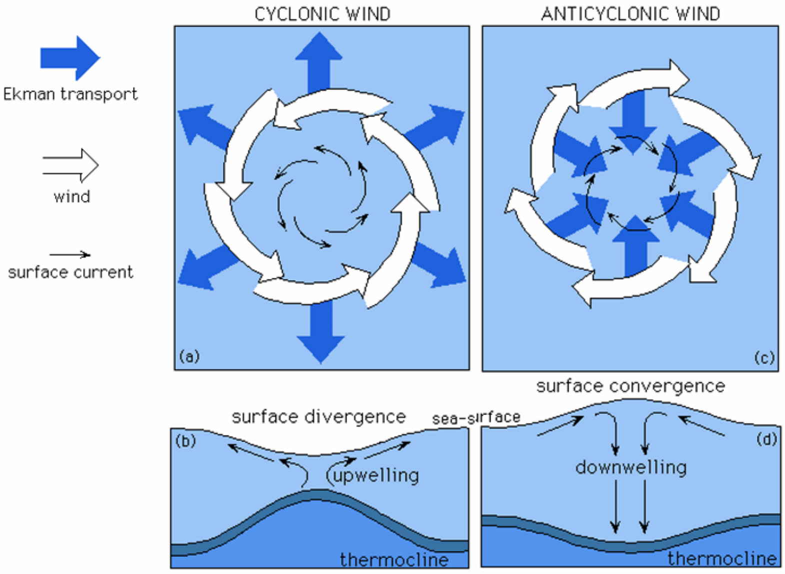
- Low pressure = cyclonic eddy (to the left on NH; to the right on SH)
- High pressure = anticyclonic eddy (to the right on NH; to the left on S H)

Within the eddies up-or downwelling results from **Ekman transport**.

- Cyclonic → Ekman transport outwards → surface divergence → upwelling of nutrient-rich water → increase in primary production (chlorophyll-a).
- Anticyclonic → Ekman transport inwards → surface convergence → downwelling

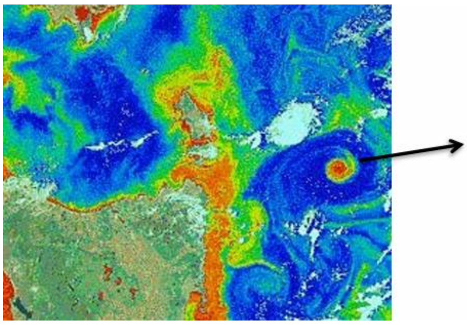
Example North hemisphere



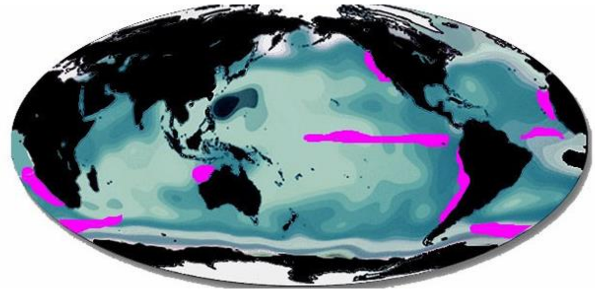


All large scale ocean gyres are downwelling.
On scales of 10-200km, eddies are result of wind patterns around L-and H-pressure systems.

Chlorophyll distribution in Tasmania:

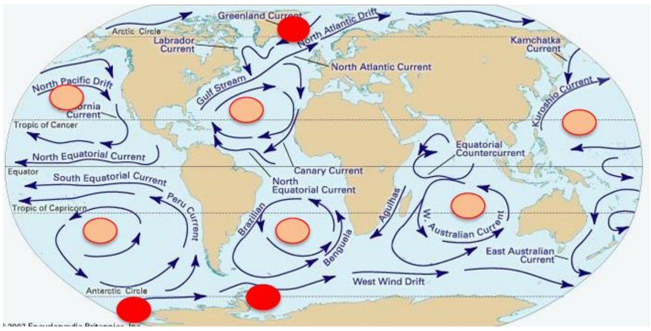


its a cyclonic eddie
(has high chlorophyll a →
lots of nutrients from upwelling)



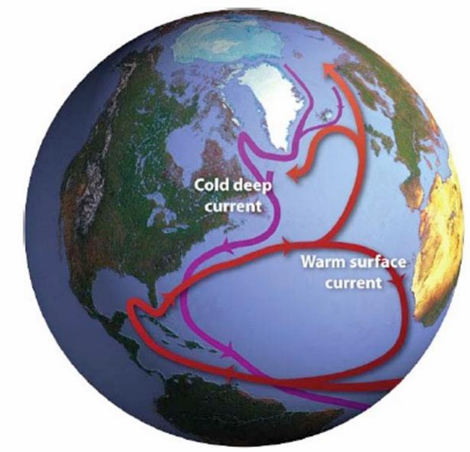
Major upwelling areas:

- Equatorial pacific
- Along Eastern boundaries of ocean basins
- Antarctic polar frontal zone



Major downwelling areas:

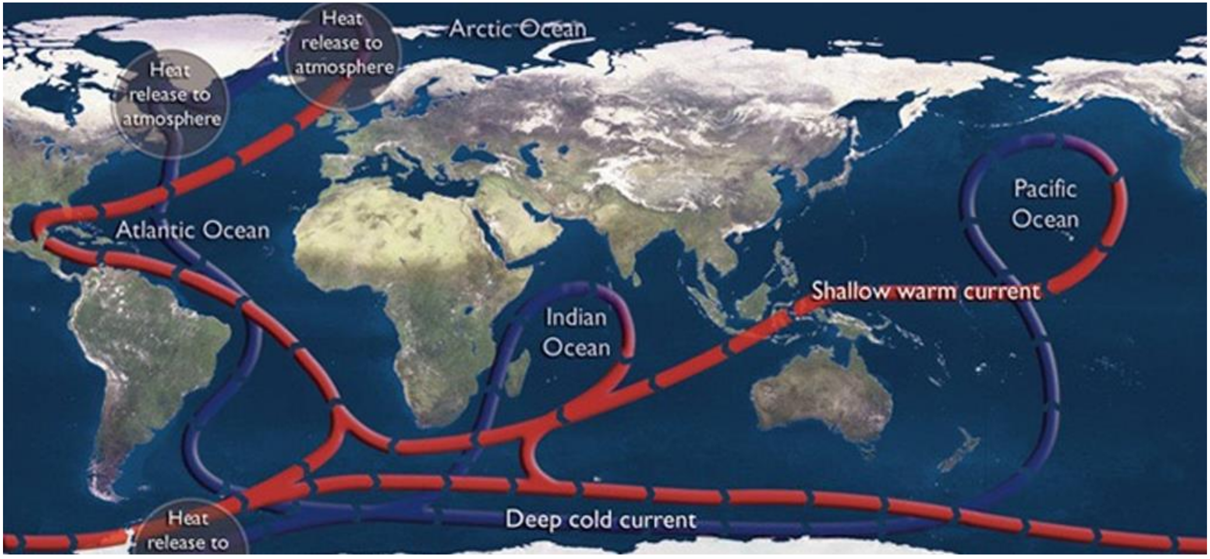
- Greenland current
- Weddell sea
- Ross sea
- Ocean gyres



OCEAN CIRCULATION:
1. wind drives surface currents
2. Thermohaline circulation (vertical), driven by exchange of heat and water (vapour) between ocean and atmosphere and by sea-ice formation near the Poles.

The Gulf stream delivers warm salty water to the North Atlantic, Where Arctic winds chill them.

Global thermohaline circulation:
Waters that sink in the N. Atlantic and Weddell Sea are the main drivers. Average turnover time: 1500 –2000 years
Ocean currents follow a fixed pattern, determined by wind, Coriolis effect, density differences and bottom topography.



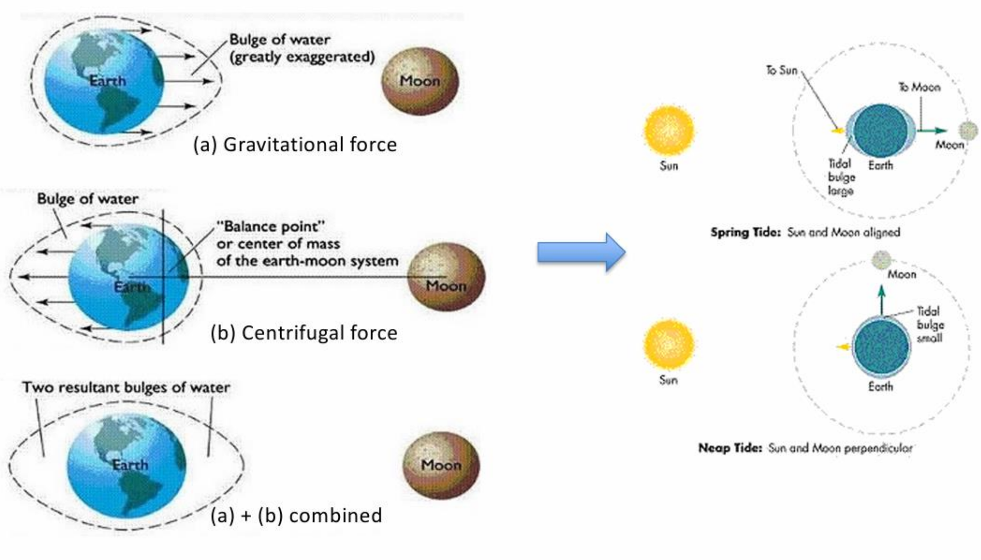
SURFACED MIXED LAYER is almost always vertically mixed to some degree. Created by:
- Wind stirring (max. depth is around 100 m)
- Cooling and evaporation (increases density→sinks → vertical mixing)
  Max. depth up to ~1000 m, but is mainly 200-300 m.

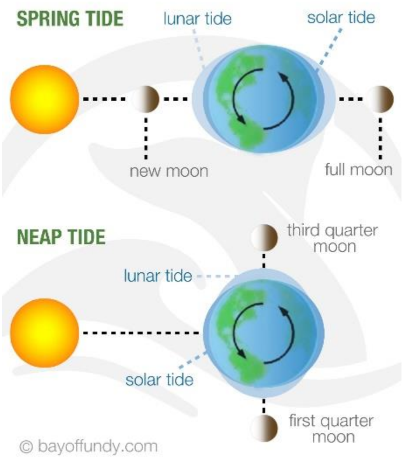
Seasonal changes:
- Summer: surface is calm + warm , sun heats the surface but there's little mixing so it stays on top→ thin mixed layer (several meters).
- Winter: storms + cold stir water deeply→ mixed layers reach maximum thickness.

Maximum Mixed Layer Depth (MLD):
The deepest mixed layers occur in late winter when winds and cold mix the water the most. Usually 20 - 200m, but in some regions >500m
1. Band in the Southern Ocean
2. Northern North Atlantic

* Phytoplankton moves passively with the water and can be mixed to greater depths due to wind mixing. Conditions for growth are different at depth then at surface → affects growth.

TIDES:


Bulge of water (greatly exaggerated)
Earth
Moon
(a) Gravitational force
Bulge of water
"Balance point" or center of mass of the earth-moon system
Earth
Moon
(b) Centrifugal force
Two resultant bulges of water
Earth
Moon
(a) + (b) combined
To Sun
To Moon
Sun
Moon
Tidal bulge large
Earth
Spring Tide: Sun and Moon aligned
Moon
Tidal bulge small
Sun
Earth
Neap Tide: Sun and Moon perpendicular

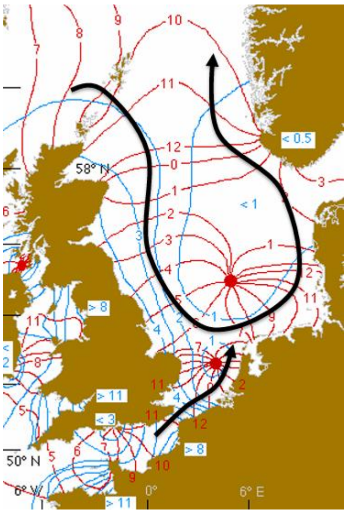


Tidal activity delivers energy in the form of high-and low-water currents.

Relatively short-lived: 2x per day (local effect, especially coastal areas).
→because there are two tidal bulges (on opposite sides of the Earth), and as the Earth spins, each location passes through both bulges once every 24 hours. That's why tidal activity happens roughly every 12 hours

A location on Earth typically experiences:

- Two high tides each day (one from the Moon-facing side and one from the opposite side)
- Two low tides each day (when that location is between the bulges).



Tidal current in the North Sea:

- Coriolis effect: forces the current towards the coast (black line).
- Turns around an amphidromic point or tidal node (spot in the sea where the tide doesn't rise or fall → tidal amplitude is zero).
  It's like a calm center in the middle of swirling water.
- The further away from this point, the greater the tidal amplitude (blue lines)

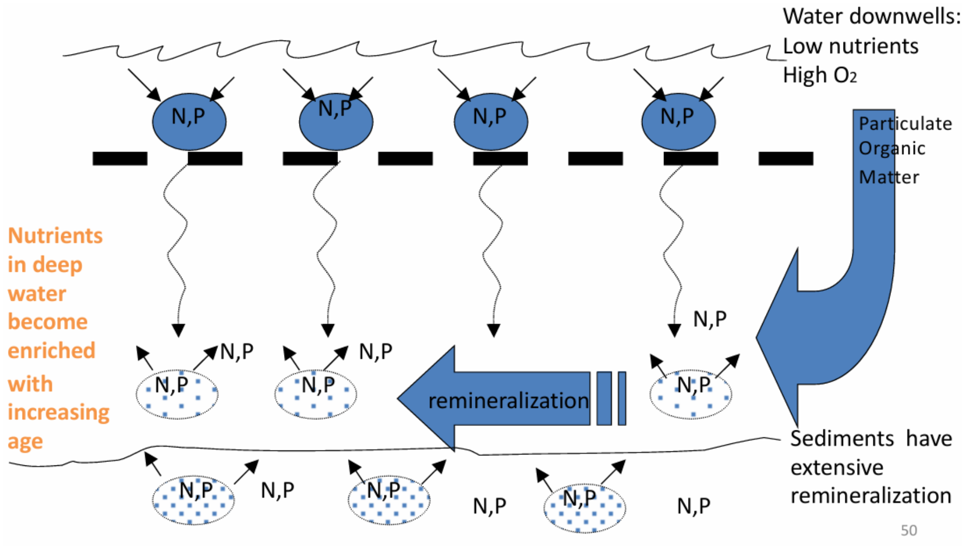
NUTRIENTS:

- Phosphate (HPO_4^{2-}): the ultimate limiting nutrient for plant growth
- Nitrate (NO_3^-): Does not limit growth of bluegreen algae (cyanobacteria) they fix nitrogen.
- Silicate (H_2SiO_4): Limits the growth of diatoms (the most abundant group of phytoplankton)
- Some micro nutrients: Zinc (Zn^{2+}), Cadmium(Cd^{2+}), Iron (Fe^{2+}), Germanium (H_4GeO_4)

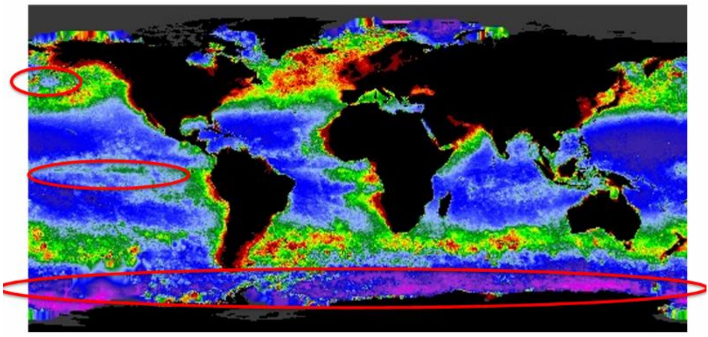
These are almost totally depleted in surface water where most of the biology goes on: their availability (or lack of it) controls growth

Control on global distribution of nutrients:

Nutrients are returned to the surface mixed layer with winter mixing and upwelling


Water downwells:
Low nutrients
High O_2
N,P
Particulate Organic Matter
Nutrients in deep water become enriched with increasing age
remineralization
Sediments have extensive remineralization
50

Differences between the oceans in vertical profiles of nutrients:
The deep Pacific has more nutrients than the Atlantic, because the waters there have accumulated more nutrients through time.



Why are in some areas nutrients not depleted?
(availability PO_4^{2-} > NO_3^{-} > H_2SiO_4)
Same areas are not depleted of diff nutrients

Annual Global Primary Production = photosynthesis by phytoplankton.
In some areas, primary production is consistently high because there's an abundance of sunlight and nutrients. However, in other areas, nutrients may accumulate because primary production is limited by other factors.

Areas of High Nutrients - Low Chlorophyll (HNLC)
Some parts have plenty of nutrients but not much phytoplankton growth because there's not enough chlorophyll (needed for phytoplankton photosynthesis)

→ In HNLC areas, nutrients remain in the water because they aren't being consumed rapidly by the primary producers.

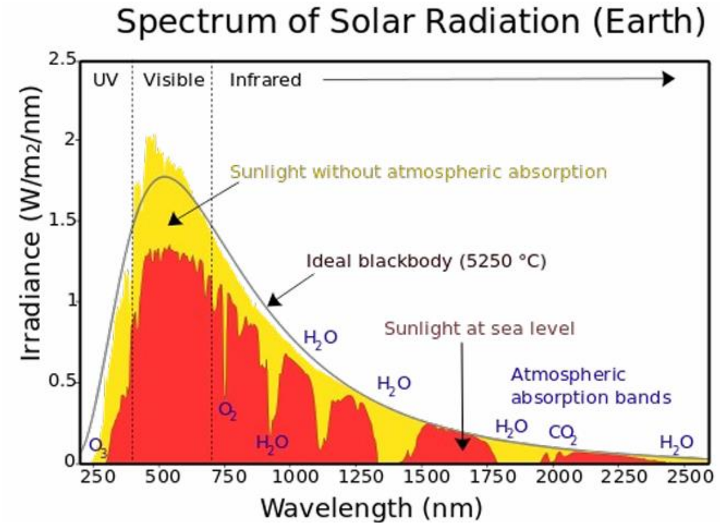
Iron limitation in large areas of the open ocean:

- Oxidized iron is not bio-available
  When iron is exposed to oxygen, it turns into **iron oxide** (rust) → isn't usable by marine life. Phytoplankton need **dissolved iron**, which is more easily absorbed.
- The main source of iron is (dessert) dust

when early life forms (cyanobacteria) released O_2, it reacted with the iron in the oceans, causing it to rust and sink (O_2 + dissolved Fe = iron oxide) delaying the buildup of oxygen in the atmosphere for millions of years.

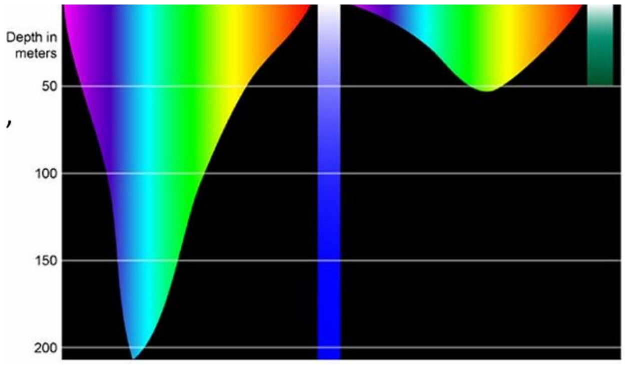
LIGHT PENETRATION:

- About half of the energy is in the visible wavelengths 400 - 700 nm.
- O3and O2 absorb much of the UV irradiance below 300 nm high in the atmosphere.
- About 70% of the visible irradiance makes to sea level.
  The rest: scattered by clouds + aerosol.
- There are large wavelength bands in which water vapor, CO2, and O3 absorb infrared irradiance.



Why is the ocean blue?

Penetration in oceans / coastal water



Water absorbs colors in the red, orange and yellow part of the light spectrum.

This leaves behind colors in the blue part of the light spectrum for us to see.
480 nm (blue) penetrates deepest into the ocean due to the high energy yield per photon.

Coastal waters can also turn greenish or reddish as light bounces off of floating sediments and particles or when blue is absorbed by chlorophyll.

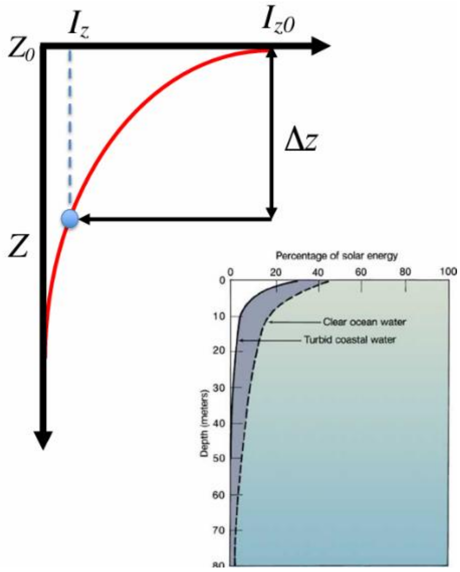
LAMBERT-BEER LAW:

The penetration of light decreases exponentially with depth and is depending on the absorption (or extinction-) coefficient of the medium:

$$I_z = I_{z_0} e^{-k\Delta z}$$

I_z = irradiance at depth z
I_{zo} = irradiance at the surface (in: Watts m^{-2} or mol photons $^{m-2}$ s^{-1})
k = extinction coefficient (depends on the constituents in the water and varies in time and space)

The more of a substance you have, and the further light has to travel through it, the more light will be absorbed → measure how much of a substance is present based on how much light it absorbs.



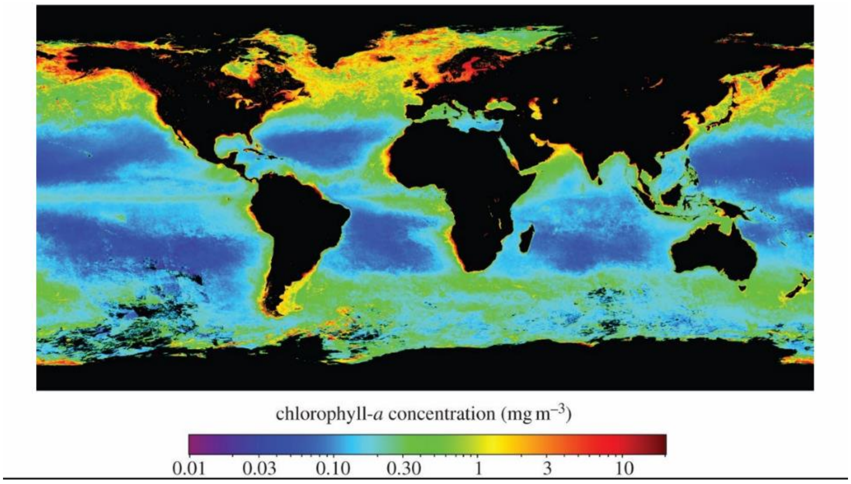
SUMMARY:

Physico-chemical parameters

- There are 4 main ocean biomes.
- Physical factors (Temperature, Salinity & Wind) result in several persistent patterns:
  - thermohaline circulation, including up- and downwelling areas
  - patterns in surface nutrient concentrations
  - depth of the Mixed Layer
  - light penetration.
- These patterns determine the boundaries and conditions of ocean ecosystems.

Question: Why is chlorophyll distributed as in the figure below? What is the limiting factor in each of the biomes?

- Near the coasts, **nutrients** are abundant, leading to higher chlorophyll levels.
- In the open ocean, the limiting factor is typically **nutrient availability**.
- In polar regions, **light** is often the limiting factor.
- In equatorial areas, **seasonal changes in nutrients** affect chlorophyll levels.



Physico-chemical parameters determine the boundaries of open ocean ecosystems:

- Global: Temperature + salinity = density → **thermohaline circulation** => connects all oceans.
- Regional: Wind + Coriolis force → **Ekman transport** => 3D circulation patterns: ocean gyres, up- and downwelling areas, eddies.
- Local: Tides.

- Nutrient distribution (N, P, Si) → HNLC regions → Fe or light limitation.
- Light → quantity and quality in relation to the **mixed layer depth**.

LECTURE 3 - OCEANS PART TWO

PLANKTON:

How can many species co-occur?
What limits primary production?
Controlling factors:

- Nutrients
- Light-Intensity-Spectrum
- Temperature

How can many species co-occur?

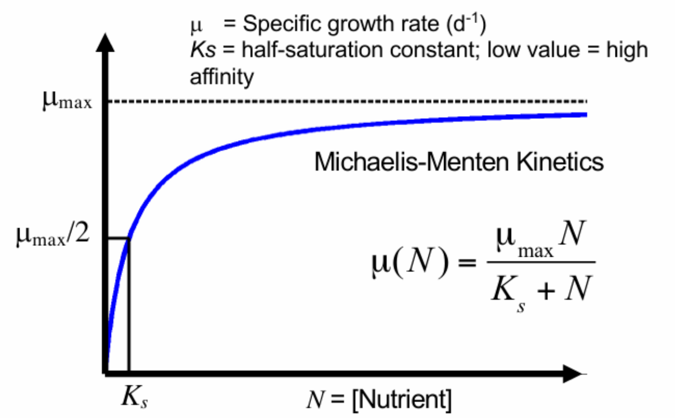
The four major players:

Diatoms - Large (2-400um) - Have silica frustules (protective glass-like outer shells)	Cyanobacteria - Small (<1um) or large colonies (0.5-4mm) - Nitrogen fixers
Dinoflagellates - Large (5-200um) - Unique life cycles & blooms	Coccolithophorids - Small (2-25um) - Have CaCO3 tests

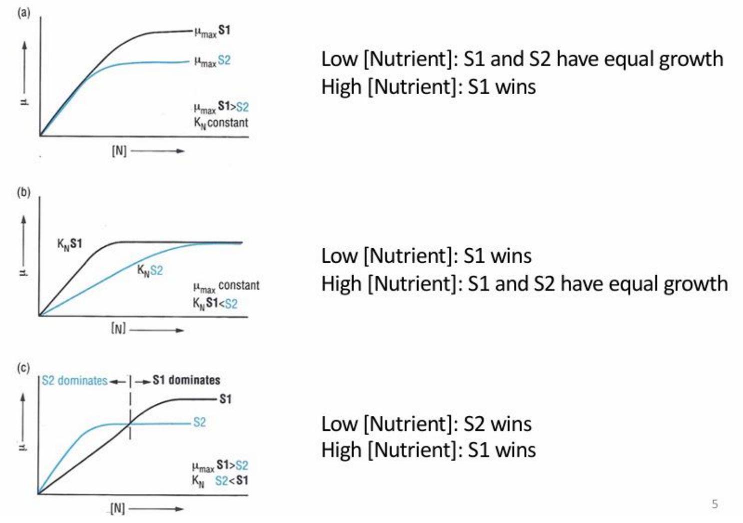
Growth conditions:

1 NUTRIENTS

Growth rate varies with [nutrient]
Species-specific μmax and Ks affect how well phytoplankton compete under different conditions.



Species have different strategies of nutrient use:

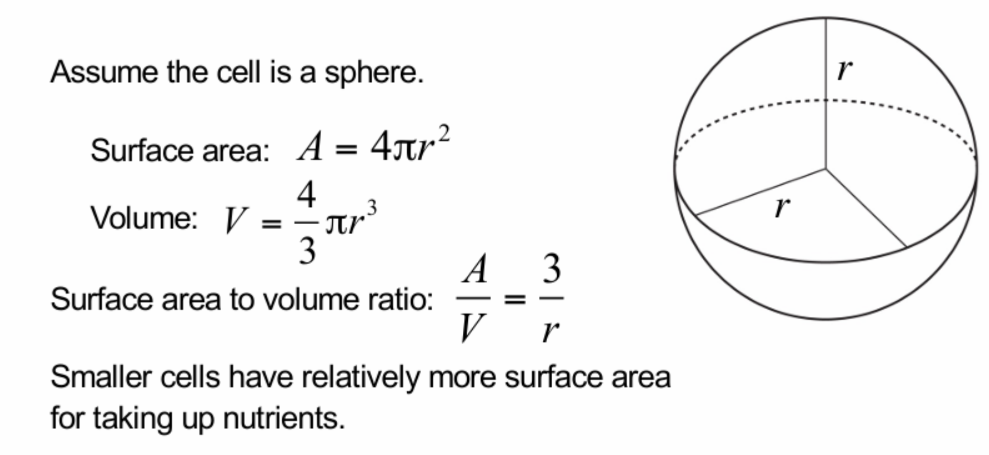


Low [Nutrient]: S1 and S2 have equal growth
High [Nutrient]: S1 wins

Low [Nutrient]: S1 wins
High [Nutrient]: S1 and S2 have equal growth

Low [Nutrient]: S2 wins
High [Nutrient]: S1 wins

Smaller phytoplankton tend to have higher affinity (= low Ks) for nutrients


Assume the cell is a sphere.

Surface area: $A = 4\pi r^2$

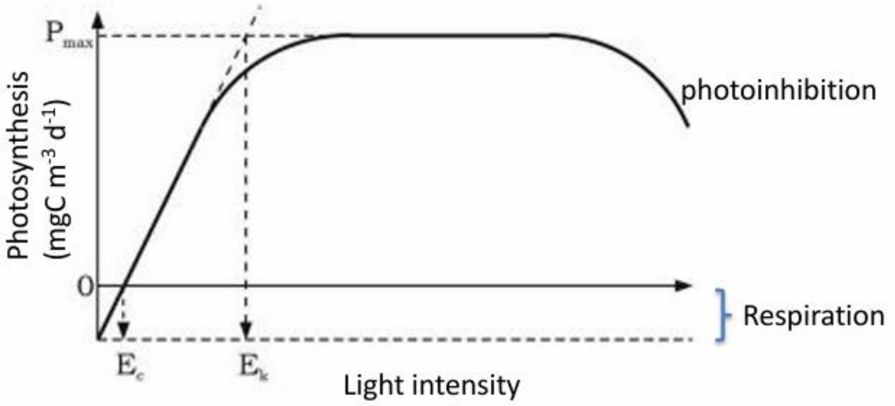
Volume: $V = \frac{4}{3}\pi r^3$

Surface area to volume ratio: $\frac{A}{V} = \frac{3}{r}$

Smaller cells have relatively more surface area for taking up nutrients.

Larger plankton (diatoms and dinoflagellates) most adapted to high-nutrient conditions.

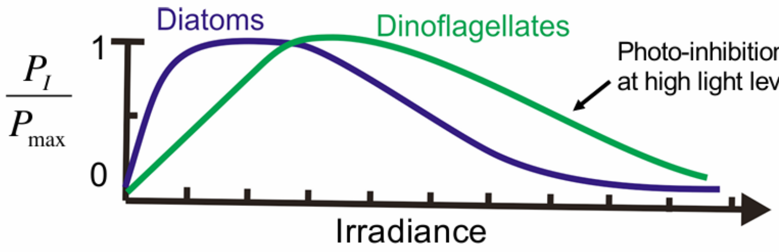
2 LIGHT INTENSITY & IRRADIANCE



* Photoinhibition + reduction in the efficiency of photosynthesis caused by excessive light.

Ec= light intensity at the compensation point (**GPP=R)**
Ek= intensity above which light is saturating for growth
Pmax= light-saturated maximum photosynthesis

Adaptation to different high levels:



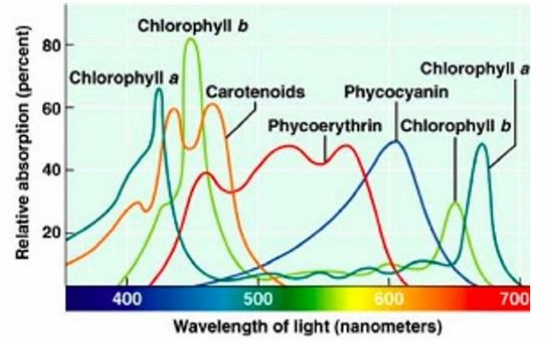
Diatoms are most adapted to low-light conditions.

3 LIGHT SPECTRUM

When the mixed layer is shallow, more wavelengths are available.

Phytoplankton absorb light using different types of pigments
- Different pigments absorb different wavelengths of light.
- Phytoplankton with multiple pigments capture more wavelengths.
- Phytoplankton adapt to the spectrum of available wavelengths.

Different pigments harvest different wavelengths of light
- All phytoplankton have chlorophyll
- Coccolithophores and diatoms have carotenoids
- Cyanobacteria have phycoerythrin, phycocyanin
- Dinoflagellate are variable depending on their symbiont



4 TEMPERATURE

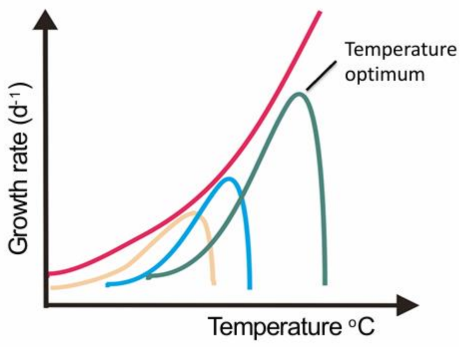
Growth-temperature curves vary among species but maximal growth rates follow a trend.

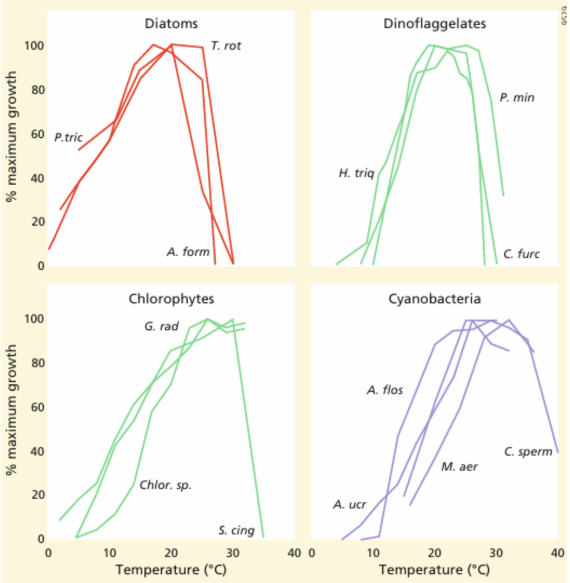
Eppley(1972) growth versus temperature relationship:

$$\mu max = 0.851 \times 1.066T$$

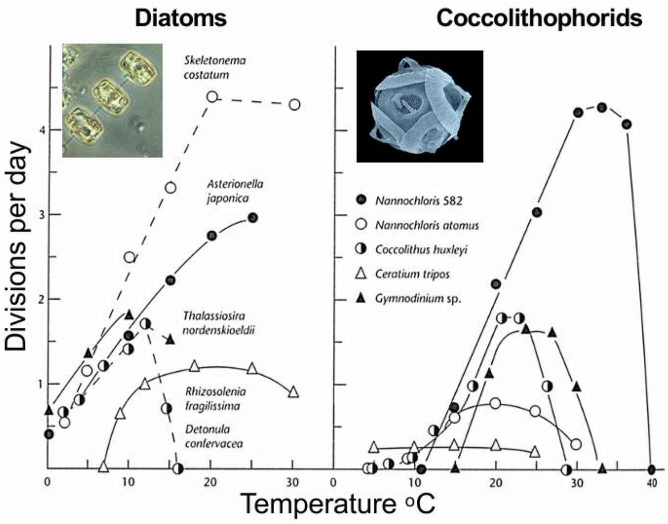
→Q10for growth = 1.88

Describes population growth (red curve)





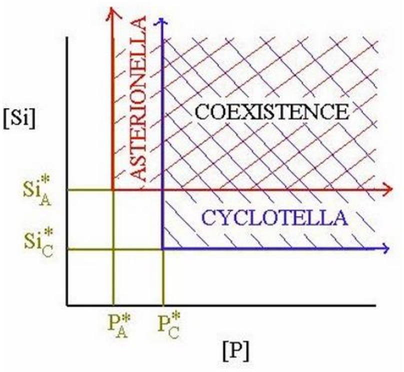
diatoms grow fastest at low temperatures



<table>
<tr><th colspan="3">NUTRIENTS</th></tr>
<tr><td colspan="2">cyanobacteria / coccolithophorids</td><td>Diatoms / dinoflagellates</td></tr>
<tr><th colspan="3">LIGHT INTENSITY / IRRADIANCE</th></tr>
<tr><td colspan="2">Diatoms / coccolithophorids</td><td>Cyanobacteria / dinoflagellates</td></tr>
<tr><th colspan="3">LIGHT SPECTRUM</th></tr>
<tr><td colspan="2">Diatoms / dinoflagellates / coccolithophorids</td><td>cyanobacteria</td></tr>
<tr><th colspan="3">TEMPERATURE</th></tr>
<tr><td>Diatoms</td><td>Coccolithophorids / dinoflagelattes</td><td>Cyanobacteria</td></tr>
</table>

Coexistence of two phytoplankton species when limited by two resources:

- Example of two diatoms with different minimum requirements (*) for silicate and phosphate.



What limits primary production?

- Nutrients
- Light (intensity + Spectrum)
- Temperature

Dependent on depth of the surface mixed layer

- Nutrients are high in polar oceans and low in the subtropical oceans.
- Light is limiting in polar oceans and saturating near the Tropics.
  * So iron limitation in HNLC areas is not the whole story

Primary Production -Definitions

CO2+ H2O -> (CH2O)organic+ O2

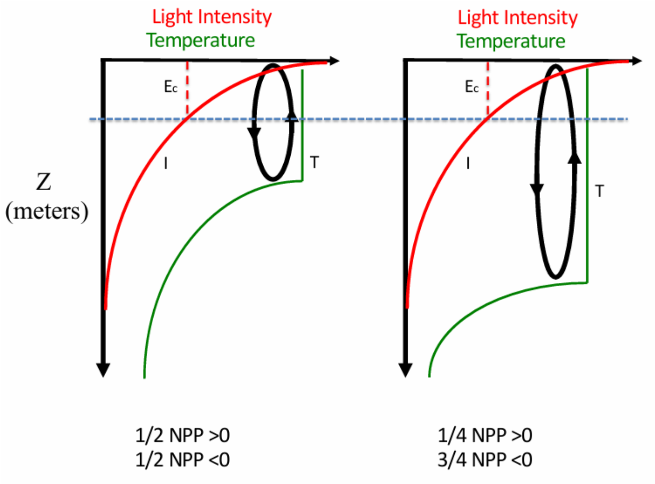
- Gross Primary Production (**GPP**) = total carbon fixed by photosynthesis (light dependent)
  units = [Mass / Volume / Time], e.g. [g C m-3y-1]

- Respiration (**R**) = rate of CO2 loss through metabolism (light independent)

- Net Primary Production (**NPP**) = GPP – R_{PLANT}

If GPP=R → NPP=0 → Compensation point (look at light intensity chart!!)

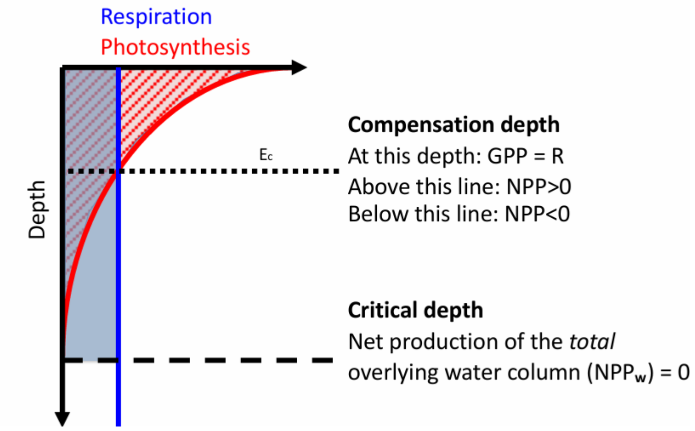
Depth of **the surface mixed layer** determines the amount of light available for phytoplankton



Ec (Critical Depth): depth where NPP becomes zero.
Above it NPP is + (photosynthesis exceeds respiration)
Below it NPP is – (respiration exceeds photosynthesis)

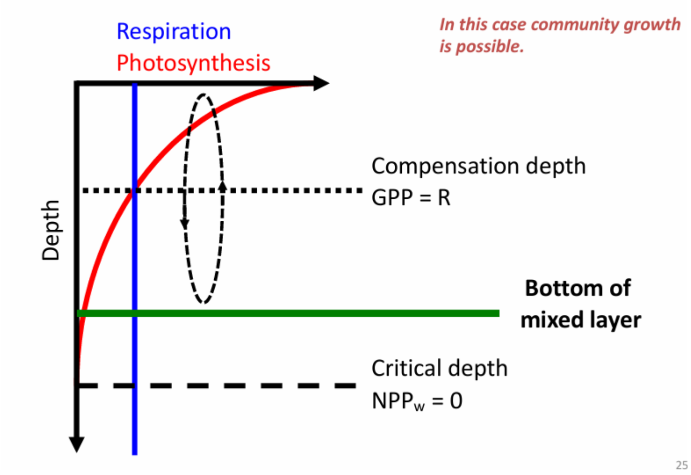
* mixed layer determined by temperature.
* photosynthesis determined by light.

Community perspective:
Compensation & Critical Depth

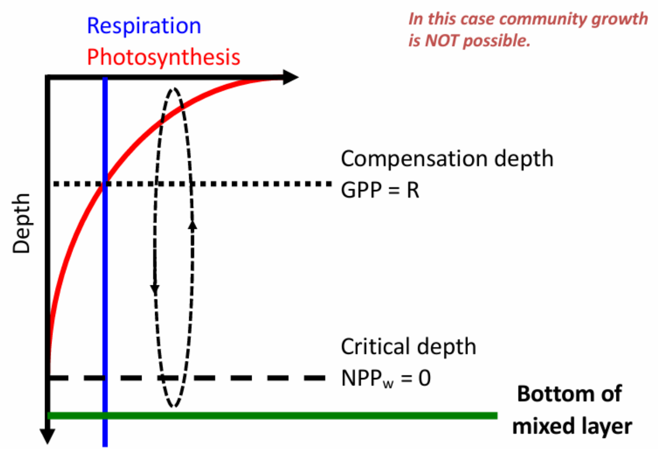


- **Depth**: individual depth point (where an individual plant/algae can break even)
- **Critical Depth**: depth where if you sum up the entire column, the total E produced via photosynthesis = total E consumed via respiration)

→ If critical depth > mixed layer depth
GPPw > Rw → NPPw > 0

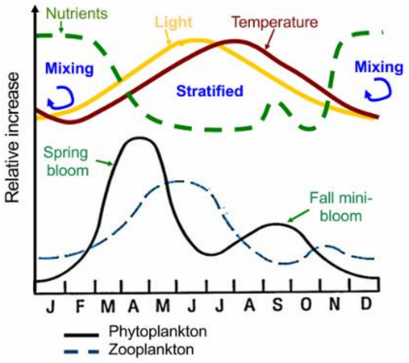


→ If critical depth < mixed layer depth
GPPw < Rw → NPPw < 0



Seasonal cycle varies with latitude:

- Polar regions: plenty nutrients (strong winds, upwelling) but only enough light in summer
- Tropical regions: enough light whole year around, but limited nutrients.



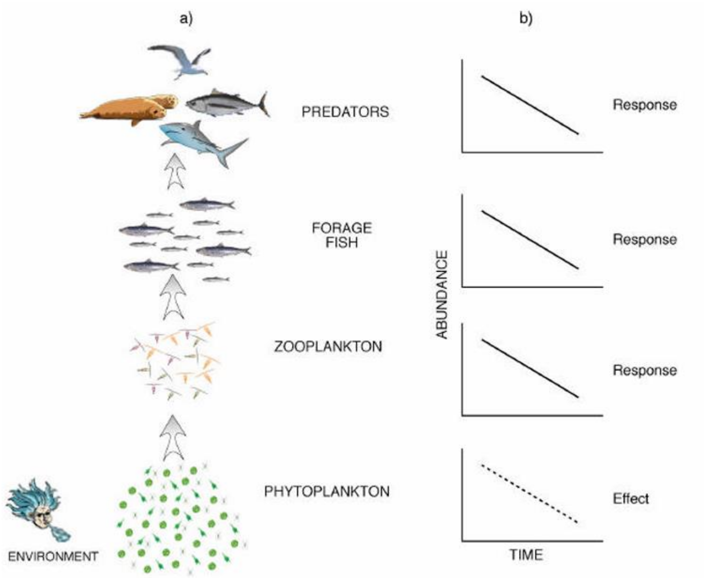
Annual cycle in temperate regions like the North Sea

FUNCTIONING OF MARINE ECOSYSTEMS:

- Control mechanisms of energy flow
- Trophic levels and energy conversion
- The global carbon cycle & the biological pump

Energy enters an ecosystem when light energy drives the reduction of CO2 to form sugars during **photosynthesis**. Organic matter and energy are tightly linked as they move through ecosystems. The energy is lost from the ecosystem when organic matter is oxidized back to CO2 by combustion or by the **respiration** of plants, animals, and microbes.

Bottom-up control:



ecosystem controlled by availability of **nutrients** + energy at base of the food chain (phytoplankton, primary producers)

more nutrients → more phytoplankton → more herbivores (zooplankton) → feeds prey → feeds predators.

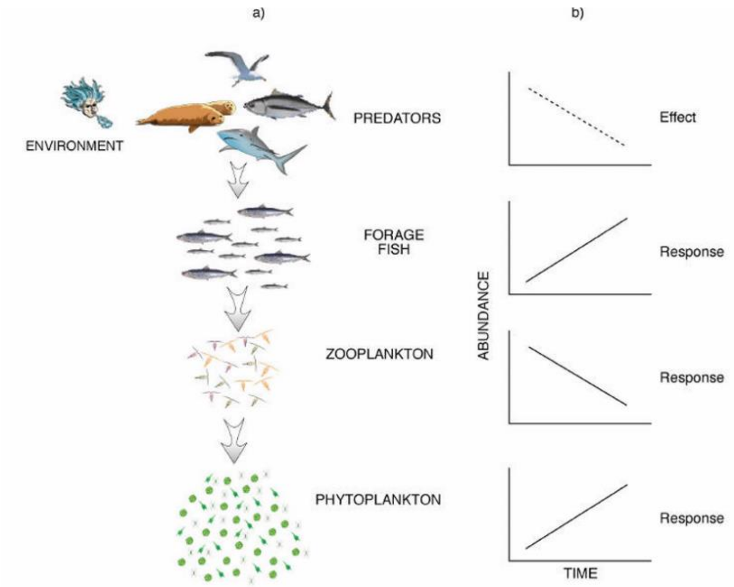
b) = response to environmental changes.

shows how a change at the bottom affects the entire ecosystem from the bottom up:

➢ phytoplankton abundance decreases over time, likely due to a change in the environment (reduction in nutrients or sunlight).

➢ This reduction in phytoplankton is the initial effect of environmental changes.

Top-down control:



ecosystem regulated by **predators** at the top of the food chain.

Environment causes...

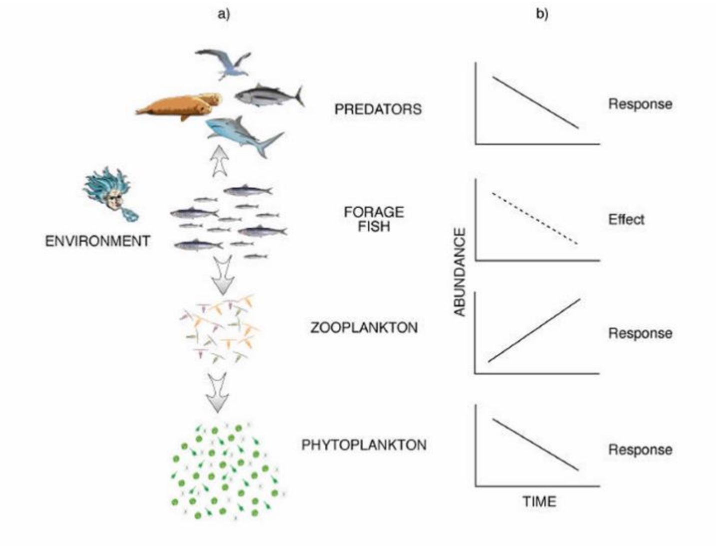
→predators decrease

→ increase population of prey

→ decrease organisms they eat (like zooplankton)

→ increase of what they eat (phytoplankton)

Wasp-waist control:



mix of top-down and bottom-up, but focuses on the middle of the food chain (small fish).

→ fishing pressure or environmental changes

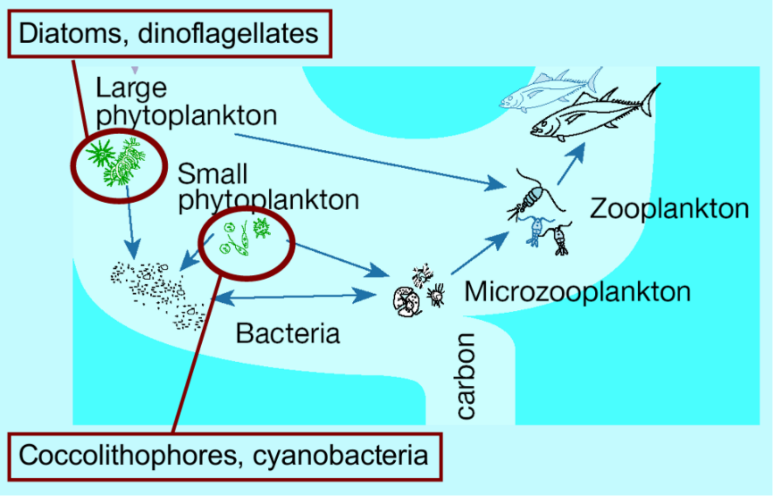
→ less forage fish

  → less predators

  → more zooplankton

→ less phytoplankton

Phytoplankton size structure



Phytoplankton: base of food web, plant-like, get energy from sunlight.
  →Large: diatoms + dinoflagellates
  →Small: coccolithophores + cyanobacteria.

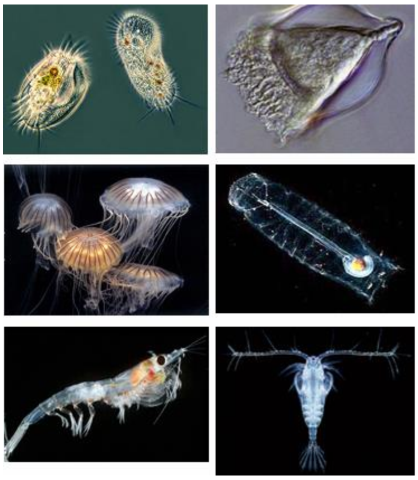
Bacteria: consume organic matter produced by phytoplankton

Microzooplankton: eat the **small** phytoplankton + bacteria.

Zooplankton: eat the small and large phytoplankton + microzooplankton.

Fish: eat the zooplankton.

Grazers of the ocean (Zooplankton)



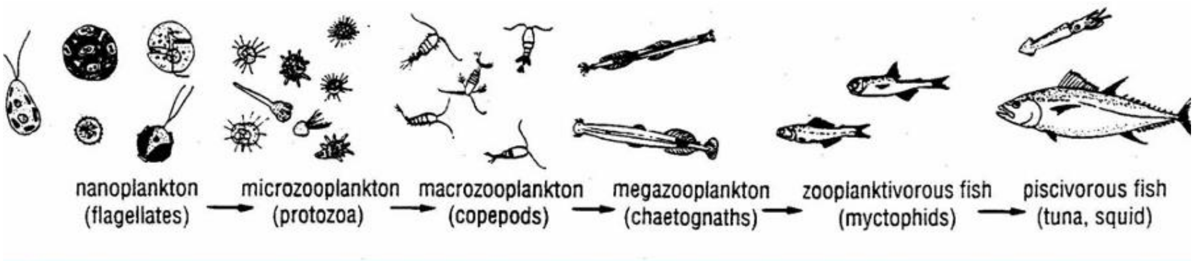
Protists-single cells
- Engulf food
- Narrow size range of food

Gelatinous animals
- “Hoover” or stick to prey
- Wide size range of food

Crustaceans
- “Handle” their food
- Narrow size range of food

TROPHIC LEVELS:

Open ocean: (5 to 6)

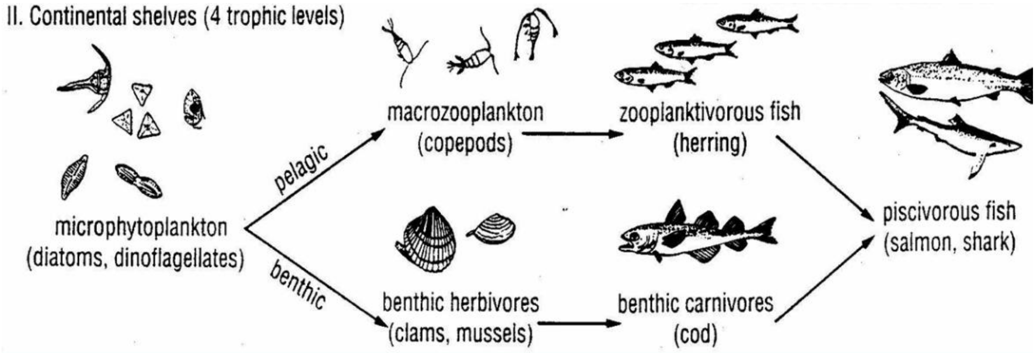

nanoplankton (flagellates)
microzooplankton (protozoa)
macrozooplankton (copepods)
megazooplankton (chaetognaths)
zooplanktivorous fish (myctophids)
piscivorous fish (tuna, squid)

Relative biomass (production) of each trophic level needed to sustain the next:

10,000 kg 1,000 kg 100 kg 10 kg 1 kg 100 g

In oligotrophic systems (very low levels of nutrients), small phytoplankton dominate and biomass goes through more levels of plankton to get to fish.

Coastal (shelf) sea (≈4 levels)

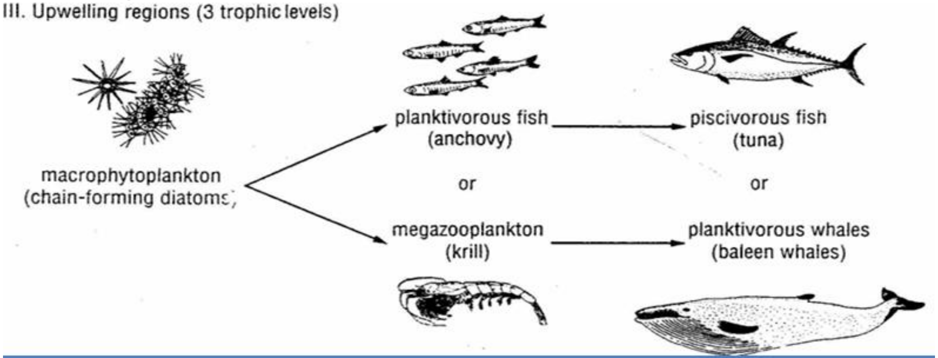

II. Continental shelves (4 trophic levels)
microphytoplankton (diatoms, dinoflagellates)
pelagic
benthic
macrozooplankton (copepods)
zooplanktivorous fish (herring)
benthic herbivores (clams, mussels)
benthic carnivores (cod)
piscivorous fish (salmon, shark)

Relative biomass of each trophic level needed to sustain the next:

10,000 kg 1,000 kg 100 kg 10 kg

Coastal areas are relatively rich in nutrients:
Shallow waters also support benthic communities

Upwelling areas (3 levels)


III. Upwelling regions (3 trophic levels)
macrophytoplankton (chain-forming diatoms)
planktivorous fish (anchovy)
or
megazooplankton (krill)
piscivorous fish (tuna)
or
planktivorous whales (baleen whales)

Relative biomass of each trophic level needed to sustain the next:

10,000 kg 1,000 kg 100 kg

Upwelling areas are relatively rich in nutrients, sufficient light and large phytoplankton.
Phytoplankton large enough to be eaten directly by larger animals.

SUMMARY:

Area	Plant Production (x 10^{12} kg carbon per year)	Transfer Efficiency	Trophic Levels	Estimated Fish Prod. (x 10^9 kg per year)
Open Ocean	39	10%	5	4
Coastal Ocean	8.6	15%	4	29
Upwelling Zones	0.23	20%	2	46

- **Bottom-up control:** mainly impact on production (carbon flux)→ When there's more food at the bottom, it increases the energy and production that flows up the food chain.

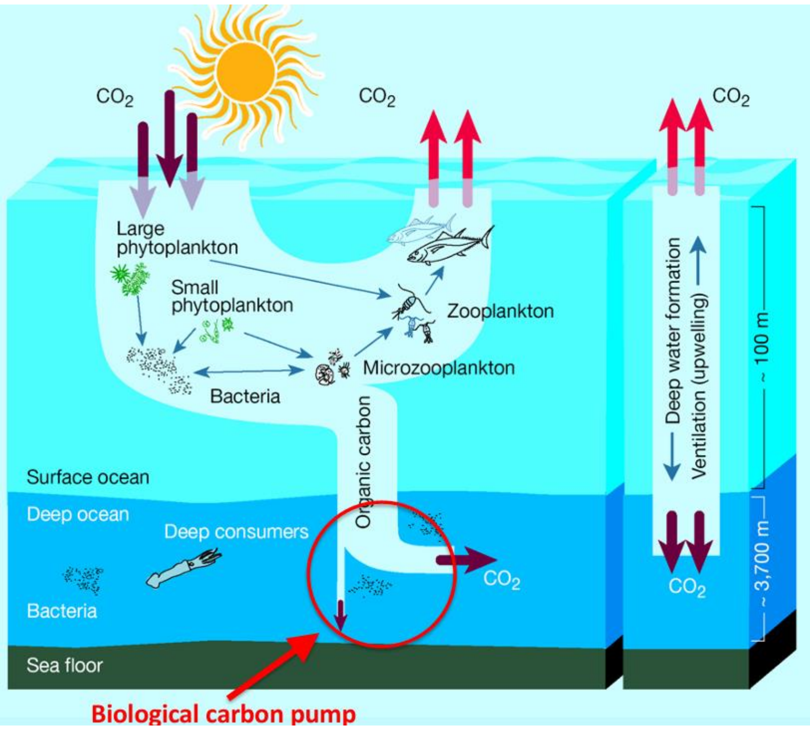
- **Top-down control:** mainly impact on biomass of lower trophic levels

- **Wasp-waste control**: often in upwelling areas with a rich intermediate trophic level

Size matters:

- Oligotrophic areas (low nutrients): small phytoplankton, long food chains, little biomass in the top levels (fewer large animals like fish)
- Eutrophic areas (nutrient-rich): large phytoplankton, short food chains, lots of fish.

BIOLOGICAL PUMP:



process by which the ocean helps to move carbon from the atmosphere to the deep ocean (reduces CO2 in the atmosphere).

- Phytoplankton absorb atmospheric CO2 via photosynthesis → converts CO2 into organic carbon.

- Phytoplankton are eaten by zooplankton, transferring carbon up the food chain.

- When phytoplankton, zooplankton (or other organism) die or release waste, this organic carbon sinks from the surface ocean to the deeper parts.

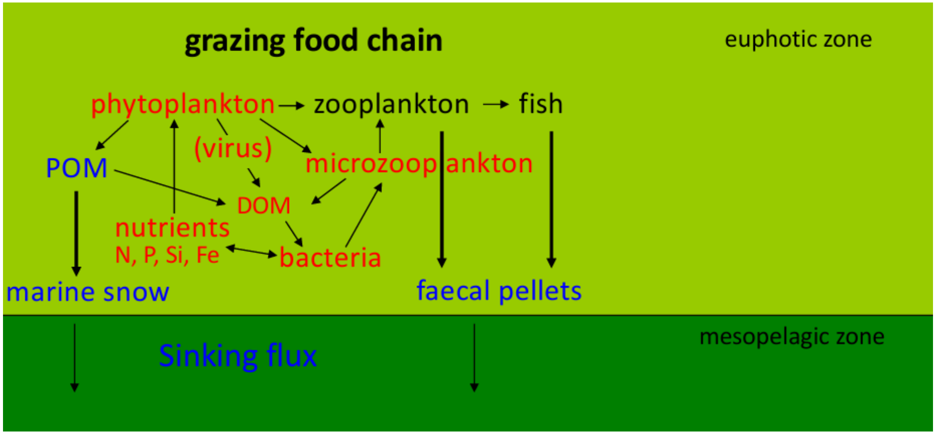
- Some of the organic material reaches the deep ocean, where it is consumed by bacteria and deep-sea organisms. Some of it gets buried in the sea floor, storing carbon for long periods.

- Not all carbon stays in the deep ocean. In places with upwelling some CO2 is released back into the atmosphere.

Organic matter has to get to the bottom of the ocean.

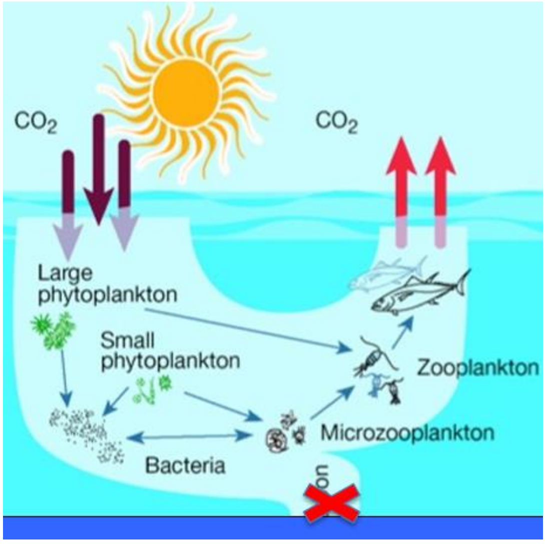
- Dead cells and fecal pellets (plankton poop) sink. Big ones sink faster.
- Dissolved organic matter, pieces of gelatinous animals etc. stick together and form bigger “marine snow” that sinks. This organic debris is collectively known as **detritus**.

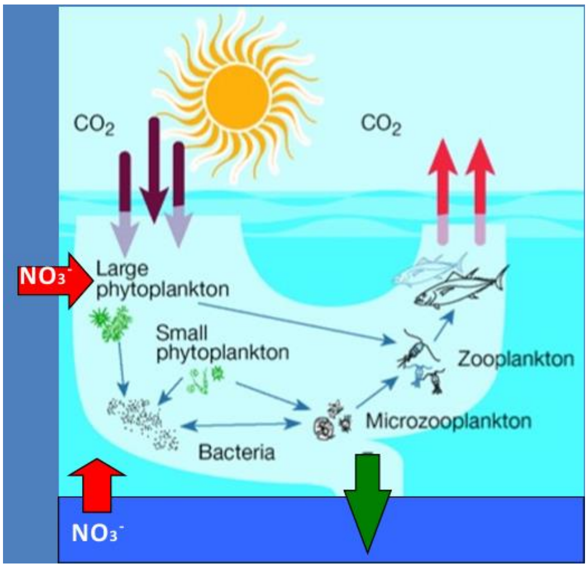
What does structure of the food web have to do with the biological pump?



The Microbial loop is interacting with the classic grazing food chain.
The sinking flux of organic matter is the so-called Biological Carbon Pump

retention vs. export system

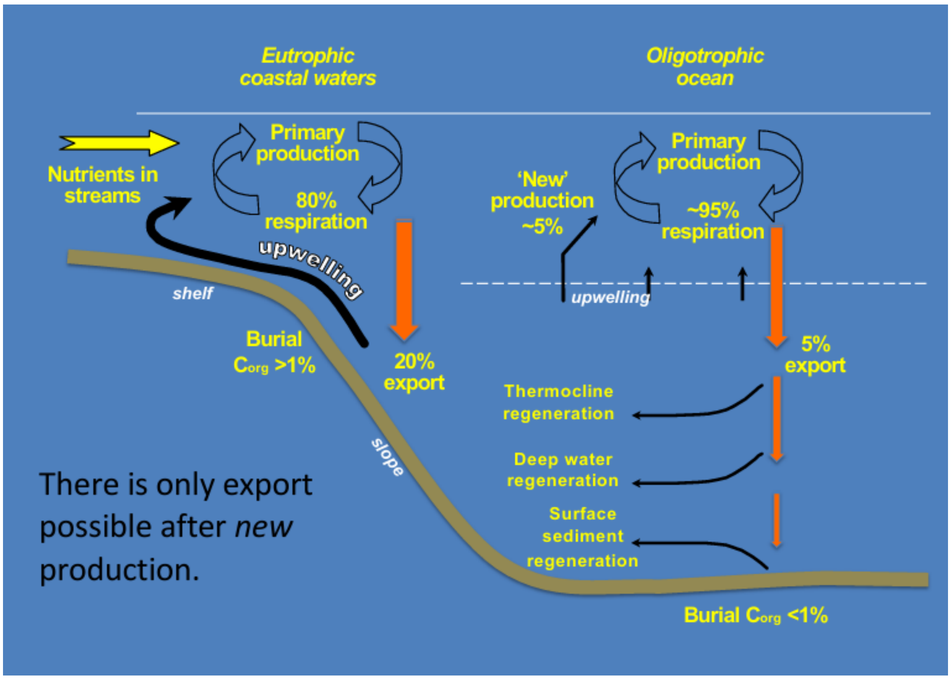




retention system:
Nutrients and C stay near the surface, supporting smaller life forms.
Microorganisms recycle nutrients in the euphotic zone;
N in the form of NH_4+
All matter is kept inside the system.

Export system:
New production supported by external nutrient input.
N in the form of NO_3^- and N_2
Larger phytoplankton grow supported by nutrients (NO3–) brought up from the deep ocean.
Some of the C and organic material sinks -→can be consumed by deep-sea organisms or stored in the ocean floor, removing carbon from the surface.

Nutrients and carbon cycled in eutrophic coastal waters (nutrient-rich) and the oligotrophic ocean (nutrient-poor)



- In nutrient-rich areas (eutrophic), more C is exported and buried because of higher primary production.

- In nutrient-poor areas (oligotrophic), most of the C is respired, and very little is exported or buried.

- "There is only export possible after new production" for carbon to be exported to deeper waters, there must be new primary production at the surface.

Eutrophic Coastal Waters:
- Nutrients come from streams and rivers → coastal areas have lots of nutrients.
- Phytoplankton use these nutrients to grow → "**primary production**."
- The carbon produced by phytoplankton is used:
  → 80% of the carbon used by organisms (**respiration**)
  → 20% exported to deeper waters.
- **Upwelling** brings deep, nutrient-rich water to the surface, helping with primary production.
- **Carbon burial**: A large amount of carbon (> 1%) is buried in sediments near the coast.

Oligotrophic Ocean:
- Limited nutrients → lower levels of new production (5%).
- Primary production:
  → 95% of the carbon produced is **respired**
  → 5% is exported to the deep ocean.
- **Upwelling**: less "new" nutrient production than in coastal areas.
- **Carbon burial**: Very little carbon (< 1%) gets buried in the deep-sea sediments because of the limited production.

Summary C-budget:

- The **Biological pump** "pumps" atmospheric CO2 into the deep sea, via organic material and is de most important mechanism by which CO2 can disappear from the system.
- A **retention system** recycles all organic material within the microbial loop. CO2 stays in the system.
- **Export of CO2** into the deep ocean can only happen when extra nutrients enter the system